

Advanced Air Bag Technology Assessment

Final Report

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April 1998

Prepared for

National Highway Traffic Safety Administration
and

National Aeronautics and
Space Administration

by

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Pasadena, California

The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the National Highway Traffic Safety Administration and the National Aeronautics and Space Administration.

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ACKNOWLEDGMENTS

In conducting this assessment the Jet Propulsion Laboratory (JPL) has had the support of many organizations that have provided advice and information on all aspects of air bag technology, biomechanics, crash dynamics, testing and other related aspects of automobile occupant protection. JPL is grateful for this support. Organizations that have been in contact with JPL are listed in Appendix A. The authors also thank the JPL Review Board members, consultants and the many individuals in industry and government who took valuable time to work with us.

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EXECUTIVE SUMMARY

1.0 NASA/NHTSA AGREEMENT

As a result of the concern for the growing number of air-bag-induced injuries and fatalities, the administrators of the National Highway Traffic Safety Administration (NHTSA) and the National Aeronautics and Space Administration (NASA) agreed to a cooperative effort that “leverages NHTSA’s expertise in motor vehicle safety restraint systems and biomechanics with NASA’s position as one of the leaders in advanced technology development... to enable the state of air bag safety technology to advance at a faster pace...” They signed a memorandum of understanding for NASA to “evaluate air bag performance, establish the technological potential for improved (smart) air bag systems, and identify key expertise and technology within the agency (NASA) that can potentially contribute significantly to the improved effectiveness of air bags.” NASA is committed to contributing to NHTSA’s effort to “(1) understand and define critical parameters affecting air bag performance, (2) systematically assess air bag technology state of the art and its future potential, and (3) identify new concepts for air bag systems.” The Jet Propulsion Laboratory (JPL) was selected by NASA to respond to the memorandum of understanding by conducting an advanced air bag technology assessment.

A NASA/NHTSA agreement to assess advanced air bag technology

2.0 THE PROBLEM

Deploying air bags in moderate-speed crashes have killed at least 44 children and 36 adults between 1990 and October 31, 1997. This should be considered, however, against the 2,620 people who NHTSA estimates have been saved by air bags during that same period. To put these numbers in perspective, there are about 90 light vehicle occupant fatalities per day from crashes and about 22 of these fatalities are in frontal crashes, where air bags are designed to provide effective occupant crash protection.

This automobile safety system is injuring occupants because of the widely variable nature of motor vehicle crashes and the performance of current air bag systems. Crashes can happen at any speed and vary widely in character and severity. The occupants to be protected are typical of the population as a whole. They include men, women, and children of all sizes and ages who may, or may not, be belted. A restraint system, such as an air bag, must respond to this highly varied and unpredictable need for protection.

The cause of air bag injury lies in the design of the air bag and the variability of the crash process

An inherent design feature of air bags is that they deploy rapidly toward occupants during a crash. This leads to their tendency to cause injuries. To deploy, air bags must burst through protective covers and expand in a very short time. The time from initial impact to full deployment must be on the order of 50 ms.

3.0 APPROACH AND OVERALL FINDINGS

Study approach

JPL's interpretation of its mandate led to the following activities. We analyzed the nature of the need for occupant restraint, how air bags operate alone and with safety belts to provide restraint, and the potential hazards introduced by that technology. This yielded a set of critical parameters for restraint systems. We examined data on the performance of current air bag technology. Finally, we searched for and assessed how new technologies could reduce the hazards introduced by air bags while providing the restraint protection that is their primary purpose.

Today's air bag is a "one-size-fits-all" system

Today's air bags are "one-size-fits-all" systems. They have crash sensors that predict the severity of crashes early in the crash event. If a crash is sufficiently severe, these sensors trigger air bag deployment by igniting a propellant in an inflator that rapidly generates gas to fill the air bag. This system has not been able to provide protection without causing injuries and deaths. Furthermore, we found an absence of a fundamental understanding of air bags as a system. If any of the automobile manufacturers or air bag suppliers have developed a systematic characterization of air bags, it was not made available to the JPL team when requested.

Keep-out zone

Air bags cause injury if an occupant is in close proximity to them when they deploy. The region of high injury risk is defined by a keep-out zone, which varies in size with the vehicle's air bag design, and with the size, position and fragility of the occupants. As long as air bags are capable of causing injury, there will be a keep-out zone. Injury risk will continue until the keep-out zone is eliminated by technology or design, or until the air bag can be disabled when an occupant is within this zone. Of course, if an air bag is disabled, it will not provide protection.

Design challenges

To improve air bags, designers have several basic challenges. Increased information about the crash and the occupants and a more tailored response are needed. First is the need for crash sensors that can more accurately estimate the need for occupant protection within about twenty-thousandths of a second after the onset of a crash. These sensors measure the dynamics of the beginning of the crash pulse and, often using algorithms, determine the need for air bag

deployment. Second, if air bag inflation is tailored for occupants, it is necessary to be able to determine the size, type and belt status of the occupant to be protected. Third, a sensor is needed to detect when an occupant is in or is entering the keep-out zone so that the air bag can be kept from inflating or can be inflated at a reduced rate. Fourth, air bags must respond to the crash type and severity, and occupant size, position and belt status. They must inflate rapidly, but consistently in time and space when they are triggered by the crash sensors. It would be useful if the rate of inflation could be controlled, at least to the extent of having dual stages of inflation for more or less severe crashes and for both belted and unbelted occupants of different sizes. As air bags inflate, the region within which they can inflict harm on occupants (the “keep-out zone”) must be minimized and restricted to regions where occupants are unlikely to be.

Can advanced technology make air bags safer and more protective? The short answer is yes, but there are significant problems to overcome.

Depowering

Improvements to air bags are already being made. The magnitude of forces from inflating air bags are being reduced in model year 1998 vehicles by depowering, i.e., reducing the inflation rate and pressure. This was permitted in 1997 by an amendment to the federal standard (FMVSS 208). Depowering will reduce the risk to small-statured drivers, out-of-position drivers and front-seat passengers. NHTSA has also permitted disconnection of air bags (either permanently or temporarily with a switch) for people who are unavoidably at risk from air bag inflation.

Improvements by model year 2001

The industry is developing a number of promising technologies to meet the air bag design challenges. By model year 2001, improved crash sensors, belt use sensors, and seat position sensors can be available to provide more information about the crash and occupants. If aggressive development is undertaken, belt spool-out sensors and static proximity sensors could be available to provide improved occupant position determination. Improvements in response include automatic suppression to prevent inflation, two-stage inflators, compartmented bags, variable venting and advanced safety belts. With these improvements will come a reduction in the keep-out zone and more tailored response which will reduce the risk of injury relative to depowered air bags.

Improvements by model year 2003

By about 2003 occupant weight and position sensors should be available to be used with sensors and response capabilities previously developed. These systems should be able to remove most of the risk of injury from deploying air bags.

Unreliability effects

However, even with the improvements that could come in 2003, there will be a small residual hazard from unintended inflations resulting from unreliability. Also, unbelted out-of-position occupants will receive no protection if the air bag is suppressed.

Advantages of safety belt use

JPL particularly found manual restraint use (safety belts and child safety seats) to be critical to addressing the problems of air bags. Furthermore, if air bag designers could assume that occupants would be belted, air bags could be designed to give superior protection with far less hazard. The growing use of safety belts may permit such a design strategy.

Technology challenges

To achieve improvements in air bag performance with advanced technology, technology hurdles need to be overcome. Air bag deployment time variability and inflator variability must be reduced. System and component reliability must achieve high levels, and occupant and position sensors must be developed.

4.0 THE TECHNOLOGICAL CHALLENGE

The technological challenge is to provide more robust occupant restraint systems, including air bags, i.e., systems that are safer and more protective over a wide range of crash severities and occupant categories. Stated simply, air bag protection must be more robust with respect to variation of critical parameters that govern air bag performance.

4.1 CRITICAL PARAMETERS

An advanced system must be better than current systems at obtaining and processing information. It will have to predict crash severity, establish the size and weight of the occupants, determine their proximity to the air bag, and sense whether or not they are belted. Air bag inflation will need to vary in response to crash and occupant variation. The parameters that determine air bag advanced technology requirements were established by a functional analysis of a complete crash scenario. The critical parameters that govern the performance of the air bag system provide information about the crash and the occupant, and the air bag response. They are:

Input Information

Critical parameters

- Crash severity and vehicle crash pulse shape and duration
- Driver and passenger characteristics including height, weight, age, and gender

- Belt or child safety seat use
- Proximity of the occupant to the air bag module

Air Bag Response Characteristics

- Time to deployment decision: sensor reaction and information processing
- Time and rate of air bag inflation, which is related to inflator parameters
- Inflator parameters, such as inflator mass flow rate
- Air bag parameters, such as configuration, compartmentalization, venting, materials, and fold

Reliability

- Reliability of the complete air bag system

4.2 AIR BAG PERFORMANCE

The performance of an air bag system expressed in terms of occupant injury risk is strongly affected by the inflator gas output characteristics and the time at which inflation is initiated, i.e., deployment time. At the beginning of a crash, an occupant begins to move forward relative to the vehicle. The distance between the occupant and the air bag module decreases as the occupant moves forward. If the deployment time is late in the crash, the occupant can be close enough to the air bag module to interact with the inflating air bag and can experience inflation-induced injuries.

Car crash testing performed by Transport Canada is discussed in Section 7 of this report. These tests show that late deployment of the air bag can occur often in “soft” crashes that resemble common vehicle-to-vehicle crashes. Their test results also show that forces on the occupant and the risk of injury increase substantially when the deployment timing (time to initiate air bag deployment) is later than about 40 ms after the crash begins.

The higher forces on the occupant can be caused by inflation of the air bag while the occupant is enveloped by the bag. This occurs as the occupant is forced forward by vehicle deceleration. An occupant can be in motion toward the air bag module or, in the case of Transport

Control of deployment time and inflator output are critical to air bag performance

Canada tests with belted occupants, restrained by three-point belts. The increasing bag pressure during inflation acts to expel the occupant from the bag and, because the bag is flexible, force the head upward and extend the neck during inflation. The level of bag pressure and the rate of increase of bag pressure is dependent on the inflator gas output. Consequently, inflator gas output and deployment time are among the most critical parameters that affect air bag performance as expressed in terms of occupant injury risk during a vehicle crash.

No systematic investigation of air bag performance

In the course of this study, we determined that the interactions among the more important parameters that govern air bag performance had not been systematically investigated and understood. To meet a goal of protecting the public from air-bag-induced injury during vehicle crashes, air bag performance must be characterized and understood (1) for occupants of different sizes who sit at different distances from the air bag module, (2) for vehicle crashes of differing severity ranging from low-speed vehicle-to-vehicle crashes to high-speed rigid barrier crashes, (3) for different ambient temperatures, because temperature has a large effect on inflator gas output characteristics, and (4) for belted and unbelted occupants. The air bag systems presently in the U.S. vehicle fleet have been optimized for the 50th-percentile male without a safety belt in a 48 km/h (30-mph) rigid frontal barrier crash at ambient temperature.

The performance of present air bag systems can be severely degraded by changes in any of the four parameters mentioned above. The introduction of advanced technology must dramatically increase the robustness of air bag system performance with respect to the variability of critical parameters encountered during public use of automobiles.

4.3 TECHNOLOGY ADVANCEMENT NEEDS

The expected improvements in safety and protectiveness of air bags, as described above, must be tempered by the understanding that there are key technology advances to be made.

Key technology development needs

- (1) Air bag deployment time variability must be reduced by improvements in the vehicle crush/crash sensor system
- (2) Inflator variability must be reduced so that dual-stage inflators can be applied effectively
- (3) System and component reliability must receive diligent attention to achieve the high levels required under field conditions

- (4) Occupant sensors must be developed that can distinguish between small, medium, and large adults, children and infant seats with high accuracy
- (5) Position sensors to measure occupant proximity to the air bag module with the required response time and accuracy must be demonstrated

All of the above are the subject of current development; but development, test, and integration of the advanced technologies needs to be accelerated to enable its incorporation into production vehicles.

5.0 ADVANCED AIR BAG TECHNOLOGY

5.1 ASSESSMENT OF AIR BAG TECHNOLOGY

Advanced occupant restraint technology is being developed in an environment that is primarily influenced by NHTSA, the automobile manufacturers (original equipment manufacturers or OEMs), and restraint system and component suppliers. NHTSA has said that it intends to amend Federal Motor Vehicle Safety Standard 208 (FMVSS 208), which governs air bag performance, in a way that is likely to require advanced air bag technology. This has set in motion a flurry of advanced development activity by both OEMs and suppliers.

The OEMs specify design parameters for the restraint systems they will use that must meet the requirements of FMVSS 208. The suppliers are the primary providers of systems and technology. The interaction between the requirements of FMVSS 208, the parameters set by OEMs, and the systems developed and offered by suppliers will determine which advanced technologies will be put into production and how soon. Business considerations will play a part in the implementation of these new technologies.

JPL found no set of generally accepted requirements for advanced air bag systems. The OEMs establish requirements with the suppliers, but neither group provided requirements for the critical parameters. Therefore, JPL developed candidate requirements for some of the critical parameters to enable an evaluation of the technologies' state of readiness.

JPL has surveyed and characterized advanced restraint system technology by visits with OEMs and suppliers (which are listed in Appendix A) and by conducting an extensive survey through the use of a questionnaire (Appendix B).

Advanced technology development environment is influenced by NHTSA, the OEMs and suppliers

JPL survey of advanced technology

Suppliers are developing advanced sensors to improve crash severity determination, to detect occupants and determine their proximity to the air bag module, and to monitor safety belt use. They are developing staged inflators to provide more appropriate air bag inflation rates for crashes of varying severity to provide more protection in severe crashes. They are also developing advanced air bag concepts that will reduce injuries caused by deploying air bags. Some suppliers are developing advanced safety belt systems. Our findings are summarized in Table 1. This table lists the technology evaluated, briefly describes the technology and its capabilities, and indicates the model year it could be available for production by the supplier. The OEMs and suppliers work together to bring technology advances into vehicles, but the OEMs will decide when a new technology is to be introduced. We estimate that an additional 1 to 3 years beyond the time shown in Table 1 could be required to introduce the technologies into vehicles.

5.2 PROJECTED ADVANCED TECHNOLOGY AVAILABILITIES

Technologies are being developed that may be available for model years 2001 and 2003. JPL projected the technology availabilities based on limited contacts with a limited number of vehicle manufacturers and suppliers. The state of the art of advanced air bag technology is in a high state of flux. The projected technologies, as well as other technologies, may advance more or less rapidly than is indicated below and in Sections 5.2.1 and 5.2.2.

5.2.1 Model year 2001. The technologies that are being developed and that may be available for model year 2001 provide both improved information and improved response.

Information

- Crash sensor/control systems with improved algorithms will better discriminate when air bag deployment is necessary for occupant crash protection, will provide better threshold control, and will determine the appropriate inflation level for two-stage inflators.
- Belt use status sensors can detect when an occupant is belted so that the air bag deployment threshold can be raised when belts are in use. (These are currently in use in some cars.)
- Seat position sensors provide an approximate surrogate measure of occupant size and proximity to the air bag module. They can be used in combination with belt status sensors to determine the appropriate inflator output.

Technologies that may be available by model year 2001

Table 1. Summary of Advanced Technology Characteristics

Technology Item	Technology Description and Function	Potential of Technology to Improve the Robustness and Performance of Safety Restraint System	Technology Maturity Readiness Date*
<i>Sensors</i> Pre-Crash Sensing	These sensors provide remote sensing (electromagnetic) for early crash severity determination.	The potential here is limited. The ability to determine obstacle inertia has not been determined. The implications of system unreliability are not defined, but they are potentially serious	These sensors could be available for MY2001.
Crash Severity Sensors	These sensors are electromechanical switches and analog accelerometers for determination of crash severity.	Critical capabilities already have been demonstrated. A move toward analog accelerometers (single point sensors) is underway. This reduces cost/complexity.	These sensors are available now.
Sensing Diagnostic Modules/Crash Algorithms	Improved algorithms are aimed at reducing discrimination times and unintended airbag deployments. Evolutionary design includes improved hardware compatible with an increased number of sensor inputs and restraint firing loops.	There is unclear potential for significant improvement. Details of current system performance are unavailable to JPL due to confidentiality concerns by companies.	Development here is ongoing.
Belt Use Sensors	These sensors determine whether or not a safety belt is being used.	Hall-type sensors have been developed.	These sensors could be available for introduction into vehicles by MY2000.
Belt spool-out sensors	These sensors aid in determining occupant size.	These sensors with seat position sensors could provide approximate information of occupant size and proximity, but JPL knows of no plan by industry for their use.	These sensors could be available by MY2001
Seat Position Sensors	These sensors could be used to estimate driver size and proximity to the air bag and passenger proximity.	These sensors would be a surrogate for occupant presence and proximity sensors, but would only provide approximate information.	These sensors could be available for MY2000.

* Technology readiness dates are those dates when production subsystems could be ready. Implementation into vehicles depends upon the OEMs' decision to include them and their technology deployment schedules, which could add one to three years to the model year readiness dates provided here.

Table 1. Summary of Advanced Technology Characteristics (Continued)

Technology Item	Technology Description and Function	Potential of Technology to Improve the Robustness and Performance of Safety Restraint System	Technology Maturity Readiness Date
<i>Sensors (cont.)</i> Occupant Classification Sensors	These sensors measure weight and presence for classification of at-risk occupants.	Weight sensors have fundamental inaccuracies and systemic errors. They have limited utility. Presence sensors show ability for occupant classifications. System reliability requirements are unclear. Child seat tags will provide the required performance. Required retrofit of existing child seats is an impediment.	MY2000 could see availability of weight sensors and presence sensors. Tags are available now.
Occupant Proximity Motion Sensors	These sensors involve remote sensing systems to provide range information between occupants and in-cabin hazards.	These sensors are useful for static OOP detection. The consequences of system unreliability are not well defined. Ultrasonic/IR systems hold the greatest promise. Utility of dynamic proximity information is not well understood at present.	These sensors could be available by MY2000/2001.
Computational Systems/ Algorithms	Such systems record all sensor signals to determine/actuate restraint system response.	These might replace upgraded crash sensor diagnostic modules, as systems requirements expand. Hardware currently is available. Utility of currently envisioned advanced algorithms has not been demonstrated.	These systems could be in use by MY2000.
<i>Inflators</i> Non-Azide Propellants	These materials replace sodium azide propellants to improve gas generant properties (i.e., they are smokeless and odorless, and have fewer particulates and lower temperatures).	These propellants have lower temperature gas with no particulates. This will permit use of lighter-weight air bag fabrics, which improve performance. Simpler inflator designs are possible.	Some non-azide propellants are now used; however, they have higher gas temperatures. Low vulnerability (LOVA) propellants should be ready for MY2000.
Hybrid Inflators	These inflators use high-pressure stored gas in conjunction with a pyrotechnic charge.	These inflators have more desirable gas generant properties (i.e., fewer particulates). There is lower variability in performance.	More use is expected by MY1999. Units with LOVA propellants could be ready by MY2000.
Heated Gas Inflators	These inflators use a combustible mixture of dry air and hydrogen gas under high pressure.	The gas generant is clean and environmentally friendly. These inflators permit use of lighter-weight air bag fabrics to improve performance.	These units are expected to be ready by MY1999.

Table 1. Summary of Advanced Technology Characteristics (Continued)

Technology Item	Technology Description and Function	Potential of Technology to Improve the Robustness and Performance of Safety Restraint System	Technology Maturity Readiness Date
<i>Inflators (cont.)</i> Multistage Inflators	These systems use two separate inflators packaged as a single unit, or two separate pyrotechnic charges with a single inflator.	These inflators permit stages of air bag deployment depending on crash severity and occupant characteristics. Inflator performance variability could overshadow the potential advantages.	Two-stage inflators could be ready for production in 1998.
Inflators with Tailorable Mass Flow Rate	These systems provide control of inflator output in near real-time.	With appropriate sensor information, this technology would permit control of air bag deployment depending on crash severity and occupant location and characteristics.	These inflators are under development.
<i>Air Bags</i> New Fabrics and Coatings	Fabrics and coatings that are more flexible, lighter in weight and have lower permeability are now available.	These fabrics permit use of lower output inflators. Lower mass should reduce punchout forces on OOP occupants. These materials simplify bag folding techniques. Lighter-weight fabrics are less tolerant of particulates and high temperature gases.	Technology has been demonstrated with inflators having low particulates and lower gas temperatures. These materials could be incorporated with hybrid inflators for MY2000.
New Woven Fabrics and Bag Construction	These materials use controlled fabric porosity and improved weaving techniques to reduce or eliminate bag seams.	Fabrics having controlled porosity with low variability could eliminate the need for discrete vent holes.	This is an evolving technology, which could be incorporated as product improvement.
New Bag Shapes and Compartmented Bags	These alternatives involve air bags with multiple compartments, which inflate sequentially. Bags expand radially during deployment.	The first compartment can be pressurized much quicker to provide early occupant protection, with subsequent compartments maintaining the restraint force. This is especially beneficial to OOP occupants.	This technology could be ready for introduction in MY2000.
New Air Bag Venting Systems	These systems provide multilevel venting systems with discrete holes and continuously variable venting designs. Continuously variable venting designs would be controlled in near real-time based on available sensor information.	These systems provide pre-determined variation in venting depending on bag pressure. They provide rapid inflation of air bags (with no venting) to reduce occupant/air bag interaction. Continuously variable systems must be developed in conjunction with sensors and control strategies.	Multilevel systems could be available in MY1999. Continuously variable systems are being developed.

Table 1. Summary of Advanced Technology Characteristics (Continued)

Technology Item	Technology Description and Function	Potential of Technology to Improve the Robustness and Performance of Safety Restraint System	Technology Maturity Readiness Date
<i>Seat Belt Systems</i> Pretensioners	This technology involves high output pretensioners to increase coupling between occupant and seat.	Maximizes ride-down distance for dissipation of the occupant's kinetic energy.	Pretensioners are in some vehicles now. Newer high output devices could be ready in MY1999.
Load Limiting Devices	Single or dual level devices provide a fixed force level over the maximum occupant excursions. Continuously variable load limiters provide a wide variation of forces.	Dual level load limiters can provide two-level selection based on knowledge of the occupant's characteristics. Further adjustability is provided by continuously variable devices.	Load limiters are in some vehicles now. Continuously variable devices could be ready in MY2000.
Inflatable Seat Belts	A portion of the standard three-point belt is inflated to augment the belt function.	These devices offer inflated cushioning and also provide some pretensioning of the seat belt. Air belts are less aggressive than air bags.	These devices could be ready by MY2001.

- Seat belt spool-out sensors could provide additional information about an occupant's size and proximity to the air bag module. These sensors were not mentioned as being part of any current industry use strategy and therefore may not be available by model year 2001.
- Static proximity (occupant position) sensors could identify occupants in the keep-out zone, but will be available only if an aggressive development program is undertaken. They would not reduce injuries to all out-of-position occupants, and they could be "fooled" some of the time.

Response

- Automatic suppression can prevent inflation when sensors determine that an occupant is in a keep-out zone where injuries could occur.
- Two-stage inflators can permit relatively soft inflation for crashes of lower threshold velocity, and full inflation when necessary for crashes of high threshold velocity.
- Compartmented air bags, radial deployments, and bags with lighter-weight fabrics may reduce the size of the keep-out zone.

- Advanced belts can improve restraint system safety and protectiveness. They may include pretensioners that can provide better coupling of the occupant to the seat for improved ride-down during the crash. Also, they can, to some degree, limit occupant proximity to the air bag module. Load limiters can also improve belt performance by reducing maximum belt loads on the occupant. (Pretensioners and load limiters are currently in some vehicles.)

5.2.2 Model year 2003. By model year 2003, there could be evolutionary changes in some of the systems and the possibility of the introduction of occupant and proximity sensors.

Information

- Crash sensor/control system algorithms will continue to be improved.
- Belt use sensors will be widely used already.
- Integrated occupant and proximity sensors could be available that would identify occupants in the keep-out zone or those who would enter it.
- Precrash sensors may be available, but their application requires further investigation.

Technologies that may be available by model year 2003

Response

- Automatic suppression to prevent inflation will be available for use with proximity sensors.
- Multistage inflators to provide more tailored responses for a variety of occupants and crash severities could be available, if needed.
- Bag designs will continue to be improved, permitting a reduction of the keep-out zone.
- Pretensioners and load limiters will be placed in increasing numbers of vehicles. Air belts will be available to improve safety belt effectiveness.

5.3 NASA TECHNOLOGY

JPL conducted a search of NASA technology that might be applicable to advanced air bags. We used two mechanisms to probe all NASA

NASA has applicable generic capabilities; two specific sensors are being developed

centers and reviewed two databases. There are many generic capabilities within NASA that could be applied to air bag development. These include sensors, computing, control systems, neural networks, algorithm development, microelectronics, simulations, propellants, propulsion, and inflatable systems. NASA's systems analysis and engineering capabilities could also be applied to a number of problems such as assessing air bag performance, developing a test program to evaluate effects of variability of critical parameters on air bag performance, and applying defect detection and prevention methodologies to enhance reliability. We identified some specific technologies that could be applied to advanced air bags, including two sensors that suppliers are currently evaluating. These are a capacitive sensor for proximity sensing and a stereoscopic vision system for proximity or precrash sensing.

5.4 NEW CONCEPTS

No new major technologies identified

The surveys of industry and NASA did not identify major new technologies or concepts. All of the technologies and concepts surveyed had been previously described in published papers, company brochures, etc., or were variations of these concepts and technologies. Improvement of restraint system safety and protectiveness is primarily one of evaluating and developing the known technology options from a total systems perspective. Perhaps this report can be a catalyst for new ideas.

6.0 ASSESSMENT OF SAFETY AND PROTECTIVENESS

6.1 ASSESSMENT METHODOLOGY

Methodology for evaluation

JPL considered several approaches to "establish the technological potential for improved (smart) air bag systems" before selecting the methodology used for this technology evaluation. Our evaluation was oriented toward engineering design to permit comparison of alternative advanced designs. Real-world crash data, as exemplified by the Fatality Analysis Reporting System (FARS) and the National Automotive Sampling System/Crashworthiness Data System (NASS/CDS) did not have data of the technical nature and detail needed to support an evaluation based on field experience.

Thus, we decided that dummy crash, sled and static test data, supplemented by simulation data was the best source of the information to support our evaluation. Our approach relates probability of injury risk to dummy response measures for the head, neck, and chest. We used dummy response measures to establish

injury risk sensitivities, as a function of the critical parameters listed above.

The figure of merit we selected for evaluating advanced technologies is the reduction in injury risk from air bag deployment. Specifically, we asked to what degree the probability of inflation-induced injury in the full spectrum of occupants and crashes could be reduced with the application of advanced technology.

To establish the merits of alternative advanced technologies, we postulated scenarios for their implementation and conducted case studies. With the current air bag systems as the base case, we postulated advanced technologies that could be available. We first compared current systems with depowered air bags. Then JPL considered alternative technologies that could be available by model years 2001 and 2003 in various configurations.

6.2 REDUCTION IN AIR-BAG-INDUCED INJURIES

With current air bag systems as the base case, JPL examined the potential for reduction in air-bag-induced injuries in (1) model year 1998 with depowered air bags, (2) model year 2001 and (3) model year 2003. For each model year, the applicable advanced technologies listed above were assessed. The reduction of air-bag-induced injuries on front-seat occupants resulting from the application of the technology was estimated, as was the remaining risk to front-seat occupants.

Effect of depowering

For model year 1998, depowering of air bags could reduce the air-bag-induced injury risk of normally seated small-statured adults. Data suggests that in lower-severity crashes, neck injury risk for small-statured drivers is significantly reduced. (However, in a high-severity crash test, neck injury risk for small-statured drivers remained unacceptably high for a depowered air bag. It is not clear if this result is due to individual design or is generic.) Also, depowered air bags will reduce the keep-out zone where deploying air bags can injure out-of-position occupants, putting fewer of the front-seat occupants at severe risk. Remaining at significant risk of air-bag-induced injury are occupants who are still out of position within the new keep-out zone, children in the right front passenger seat, and infants in rear-facing child seats (RFCSS) and forward-facing child seats (FFCSs).

Compared to depowered air bags, the application of advanced technologies in model year 2001 will further reduce the size of the keep-out zone, which reduces the risk to front-seat, out-of-position

Improvements with technology available by 2001

occupants. This reduction will be due to less aggressive air bag response resulting from improved air bag design and dual inflators that provide more tailored responses. The risks to belted front-seat occupants with these second-generation systems will be reduced because of reduced air bag aggressivity, an increase in the threshold velocity for deployment, and improvements in belts. The risk to unbelted front-seat occupants will be similarly reduced by the changes in air bag performance. Despite these improvements, some OOP front-seat occupants will remain at severe risk from deploying air bags, as will children in the right front passenger seat and infants in RFCSs and FFCSS in the right front passenger seat.

Improvements with technology available by 2003

For model year 2003, further advanced technologies that could be incorporated include more sophisticated integration of proximity and occupant position sensors. The system could then suppress inflation when it has a high likelihood of injuring an occupant in the keep-out zone and provide an appropriate signal for multistage inflators. Further advances in belt and air bag design could be introduced in this time frame.

Effect of unreliability

With these technologies, the only serious risk of air-bag-induced injuries would come from the unreliability of the system. System unreliabilities are expected to result in tens to hundreds of unintended deployments per year. These unintended deployments could have the potential of causing a few serious injuries per year.

Child seats

In the summary above, the resolution of the child seat problem is projected to be achieved in the 2003 time period or after. This is based on the requirement for implementation of reliable occupant presence sensors. One manufacturer (Mercedes-Benz) currently provides a tag-based child seat detector that automatically suppresses the air bag. Such a system could be used in other vehicles, but it must be used with specific tags attached to the seats. The problem of applying these tags to the different seats being offered and retrofitting them to older seats creates significant potential for misuse. The introduction of such a system would have to be carefully controlled.

6.3 INCREASED PROTECTIVENESS

During this assessment, the evaluation of the capability of advanced technology to increase the protectiveness of the occupant protection system was a secondary priority. However, the following observations can be made:

Depowered air bags will reduce the inflation-induced injuries for small-statured and fragile adults. However, they may also reduce

Effect of depowering

the protectiveness of air bag systems for very large occupants and occupants in high-severity crashes, but JPL had no data to assess this premise quantitatively.

Effects of suppressing the air bag

Strategies used to reduce air bag inflation-induced injuries include suppression of the air bag deployment. Clearly, strategies used to reduce inflation-induced injuries that result in the suppression of the air bag leave occupants unprotected if they are unbelted.

Improvements with technology available by 2001

Technologies that are expected to be implemented in model year 2001 have the potential for increasing air bag protectiveness by providing improved sensing that permits an improved air bag response. The capability that sensors provide permit the use of dual-stage inflators that will offer increased protection to very large adults and occupants in high-severity crashes when compared to depowered air bags. The higher-level inflator stage offers that increased protection. Advanced safety belts will provide increased protection by better coupling of the occupant to the vehicle (pretensioners) and reduced decelerations (load limiters).

In model year 2003, protectiveness will be increased further by refinements in the air bag response capabilities and additional safety belt improvement.

Data were not available to quantitatively assess the combinations of circumstances where air bags might be expected to enhance protection.

System unreliability effects

System unreliability may result in unintended nondeployments and occupants will be unprotected. Based on projected air bag installation and expected 0.9999 to 0.99999 system reliability, the number of unintended nondeployments will be in the tens per year. High system reliability is achievable through diligent effort; the actual number of unintended nondeployments will depend on the effort made to achieve high reliability.

In an advanced restraint system the desired air bag system response will be tailored to perceived occupant and crash attributes in an attempt to enhance the safety and protection of the air bag. However, this more complex decision structure creates additional categories of incorrect air bag system response, i.e., deployment may be desired in a given crash and the air bag may deploy, but it may do so in a way that is tailored to the wrong response state due to misperceived occupant/crash attributes.

Effects of complexity and crash prediction

Crash attributes may be the most difficult to reliably perceive since they are necessarily a prediction of an extremely stochastic event whose attributes are generated during the event. To the extent that perceived occupant/crash attributes produce a different tailored response than the true attributes, air bag safety and protection can be adversely affected. Even ignoring economic issues, it is a major challenge to create a crash prediction system that is sufficiently accurate to rely on for tailored air bag response.

Air bag applications could be more successful if predicated on belt use

Safety belts are the primary and most effective occupant restraint system, and they are used by a large majority of occupants. Safety and protection for belted occupants is likely to be substantially enhanced if advanced air bag designs can be predicated on the use of advanced safety belts, and not compromised by accommodation for protection of unbelted occupants. The growing use of safety belts may permit such a design strategy.

7.0 CONCLUSIONS

To list the conclusions here would be to repeat many of the statements in the previous pages of this summary. Consequently, to avoid unnecessary duplication the reader is referred to Section 9 of the report for the specific conclusions.

8.0 RECOMMENDATIONS

Recommendations are directed to NHTSA and industry, including actions that require their cooperation.

8.1 NHTSA

8.1.1 The Need for a Better Understanding of Restraint System Performance. This assessment revealed activities that will require further study. Also, data required to conduct important analyses were not available to JPL. As a consequence, JPL recommends the activities described below.

- (1) Continue restraint system assessment, with emphasis on restraint protection, and include consideration of costs and benefits.
- (2) Evaluate and quantify, to the extent possible, the benefits of applying advanced technology to improve safety and protection of restraint systems with respect to injury risk of the full spectrum of occupants in the full range of crash severities experienced by the public. The benefits, costs and

risks of advanced technology should be investigated and understood with respect to injury to head, neck, chest, and other body regions across the full range of occupant categories and crash severities.

- (3) Expand the assessment of advanced technology to crashes other than the frontal crashes that were the focus of this assessment.
- (4) Develop a systematic vehicle test protocol that (a) incorporates measurements for comprehensive injury risk evaluation (head, neck, chest, etc.) for the 5th-percentile female, 50th-percentile male, and 95th-percentile male drivers as well as the full spectrum of passengers, and (b) includes crash severities representative of the full range of the “real-world” collisions.
- (5) Evaluate the impact on air bag performance of deployment time variability, inflator variability and system and component reliability for any advanced technology. Again, the full range of occupant size and crash severity that represent use by the general public must be considered.

8.1.2 The Need for Better Real-World Data. The recommendations that follow result from the deficiencies of the real-world data that are available for diagnosis of safety problems or the support of safety engineering analyses. These data were insufficient for use in this assessment. Efforts should be undertaken to:

- (6) Expand the National Automotive Sampling System (NASS) and revisit the question of how it should be structured and what procedures should be used to provide data needed for safety diagnosis and engineering analysis.
- (7) Study the feasibility of installing and obtaining crash data for safety analyses from crash recorders on vehicles. Crash recorders exist already on some vehicles with electronic air bag sensors, but the data recorded is determined by the OEMs. These recorders could be the basis for an evolving data-recording capability that could be expanded to serve other purposes, such as in emergency rescues, where their information could be combined with occupant smart keys to provide critical crash and personal data to paramedics. The questions of data ownership and data protection would have to be resolved, however. Where data ownership concerns arise, consultation with experts in the aviation community

regarding the use of aircraft flight recorder data is recommended.

8.1.3 The Need for a Better Understanding of the Future Potential of Technology. NHTSA is routinely briefed by suppliers and OEMs on the development of advanced technology and conducts independent evaluations of important advanced technologies. We therefore recommend that NHTSA:

- (8) Evaluate specific technologies that have promise of significant safety benefit, such as:
 - Precrash sensors—both separate and coupled with the crash-avoidance sensors now being investigated—which could provide improved crash type and severity sensing
 - Advanced belt systems and air belts that could improve protection, but have been neglected because of the emphasis on air bags
 - Air bag/inflator designs that could eliminate the keep-out zone and the information (sensors) required to support the functioning of the design

8.2 THE NEED FOR CONTINUED ADVANCED TECHNOLOGY DEVELOPMENT BY INDUSTRY

It is industry's responsibility to provide safe and protective vehicle restraint systems, and to develop the technology to create these systems. We recommend that industry:

- (9) Continue diligent efforts to implement the advanced technologies that have been shown to JPL, because those technologies will make restraint systems safer and more protective.
- (10) Reduce the deployment time and inflator mass flow variabilities; otherwise these variabilities will have detrimental effects on advanced air bag system effectiveness.
- (11) Continue diligent efforts to increase restraint system reliability.

8.3 NHTSA/INDUSTRY COOPERATIVE EFFORTS

- (12) Develop quantitative goals for safer and more protective restraint systems that address air-bag-induced injuries and protection in high-severity crashes.
- (13) Continue to develop and refine biomechanical injury criteria for restraint systems using the best science available.
- (14) Develop protocols and procedures for testing air bag systems to ensure air bag system robustness.
- (15) Inform the public of the specific risks associated with each vehicle air bag, e.g., by providing the keep-out zone dimensions, and recommend ways to mitigate the risk.

SECTION 1—INTRODUCTION

1.1 SYMPTOMS OF A PROBLEM

Since automobile air bags were developed, both experts and the public have become increasingly concerned about deployment-induced injuries and fatalities. Deploying air bags in relatively low-speed crashes have killed 49 children and 38 adults between 1990 and October 31, 1997; 14 of the adults were small-statured females.

Deploying air bags have caused deaths and injuries

These deaths occurred when children or adults were well within the path of the deploying air bag. Some of the children were in rear-facing child seats, or were improperly restrained in child safety seats. Most of the other people were unbelted or improperly belted and slid or leaned forward during braking, which put them directly in the path of the deploying air bag. Deploying air bags have also caused numerous injuries, some of them serious.

The 87 air-bag-induced fatalities should be compared with the 2620 lives that the National Highway Traffic Safety Administration (NHTSA) estimates to have been saved during that time period. A significant number of those survivors, however, suffered severe injuries. To put these numbers in perspective, there are about 90 light vehicle occupant fatalities per day from vehicle crashes and about 22 of these fatalities are in frontal crashes, where air bags are designed to provide effective occupant crash protection.

Application of advanced technology to improve air bag safety

The fact that an automobile safety system is causing fatalities and injuries (and that there is increased public attention being brought to the problem) has heightened the effort to seek solutions to it. Industry, the federal government, and other organizations are making serious efforts to solve the problem of air-bag-induced injuries. These efforts include education of the public about air bags, improved labeling, encouragement of safety belt use, on-off switches and the reduction of air bag energy levels (depowering). Automobile manufacturers and their suppliers are developing advanced technologies that are intended to reduce air-bag-induced injuries and improve the effectiveness of restraint systems.

Looking toward the potential of advanced technology to improve air bag safety and effectiveness, the administrators of NHTSA and the National Aeronautics and Space Administration (NASA) met and agreed to work cooperatively on the problem. They recognized that “cooperation between the two organizations can expedite technology advancements.”

1.2 MEMORANDUM OF UNDERSTANDING

NASA and NHTSA agreed to cooperate in applying advanced technology to improve air bag safety

In mid-December 1996, the Administrators of the NHTSA and NASA signed a memorandum of understanding for cooperative work with the following purpose:

“Both agencies agree that cooperation which leverages NHTSA’s expertise in motor vehicle safety restraint systems and biomechanics with NASA’s position as one of the nation’s leaders in advanced technology development including sensors, microelectronics, propulsion technologies, and systems analysis can significantly contribute to NHTSA’s effort to: (1) understand and define critical parameters affecting air bag performance, (2) systematically assess air bag technology state of the art and its future potential, and (3) identify new concepts for air bag systems. Such cooperation will enable the state of air bag safety technology to advance at a faster pace to provide timely solutions to this safety-related problem.”

The terms of the agreement are:

JPL was selected by NASA to evaluate air bag performance, establish the technological potential for improved performance and identify expertise and technology within NASA that could significantly improve air bag effectiveness

- A. NHTSA and NASA will cooperate in the development of countermeasures to reduce potential injury from air bags while enhancing their effectiveness in crash protection.
- B. NHTSA will define the technical issues associated with potential air bag injuries and be responsible for overall countermeasure development.
- C. NASA will designate a NASA facility and responsible individual as the focal point for cooperation with NHTSA. NASA will evaluate air bag performance, establish the technological potential for improved (smart) air bag systems, and identify key expertise and technology within the agency that can potentially contribute significantly to the improved effectiveness of air bags.
- D. Under separate agreements, NHTSA will cooperatively fund technology assessment studies and mutually selected activities at NASA centers that can potentially contribute significantly to the reduction of potential injuries from air bags.

The NASA Administrator assigned the Jet Propulsion Laboratory (JPL) as the focal point for cooperation with NHTSA, including the

task of assessing air bag technology. JPL planned the assessment effort and initiated work in February 1997.

1.3 CHALLENGE

The injuries and fatalities resulting from air bag deployments are symptoms of the underlying problems with air bags. The problems are rooted in the basic characteristics of air bags and the high degree of variability and broad range of crash parameters.

The problems are rooted in the fundamental characteristics of air bags and the unpredictable and variable crash environment

- Air bags deploy rapidly and with great force toward an approaching occupant. A significant engineering design challenge is to provide crash protection without hazard from the deploying bag. As currently designed, occupants in the path of the deploying air bag can be severely injured.
- The deployment of air bag systems is based on predictions of crash severity. The deployment timing is based on tests of a spectrum of crash types. However, a vehicle must respond to a wide range and variety of crash parameters in the field that cannot be replicated in any practical test program.
- Both the vehicle and air bag system responses are variable. Vehicle response is variable even for a particular crash scenario. The air bag system response is variable particularly in deployment time and inflator output.

For these reasons, current air bag systems, which provide protection over a wide range of crash scenarios, can cause injuries. That is, their designs are not robust to the needs of the operating environment. The challenge is: how can advanced technology and design improvements increase the robustness of air bag systems? Considering the above underlying problems, JPL interprets the assignment of the NHTSA/NASA memorandum of understanding as a challenge to assess the potential for advanced technology to:

The challenge is to reduce the injury risk from air bags while also improving their effectiveness

- (1) Reduce the deaths and injuries caused by air bags, and
- (2) Improve the overall effectiveness of restraint systems to reduce the approximate 8000 fatalities per year resulting from direct frontal crashes of light motor vehicles.

This challenge is the basis for the assessment objectives.

1.4 OBJECTIVES

1.4.1 Primary Objective. Identify and characterize advanced air bag technology that effectively protects occupants while eliminating the adverse effects of air bag deployment during frontal crashes—particularly on children, small adults, and the elderly—and recommend technology development needs.

1.4.2 Secondary Objective. Identify and characterize advanced air bag technology for protecting occupants from a variety of crash scenarios, and recommend technology development needs.

Note: At the initiation of the assessment, it was expected that some work would be done with regard to the secondary objective; however, this was not possible with the time and funds available.

1.5 CONSTRAINTS

The focus of the assessment is on applying advanced technology to air bags and restraint systems. The assessment did not:

- Address regulator / issues, rule-making, product liability, legal issues, or government policy
- Include technology development or testing
- Include crash tests, air bag experiments, or high-fidelity simulations

JPL relied on NHTSA, Transport Canada, and industry for biomechanics information associated with vehicle crashes.

1.6 ASSESSMENT PRIORITIES AND SCOPE

Because the primary problem that brought NHTSA and NASA together in this cooperative effort was the concern about fatalities and injuries caused by air bags, the first priority of this investigation was to assess the capability of advanced technology to reduce this problem. It is probable, however, that there is greater long-term benefit from the application of advanced technology to increase the overall effectiveness of occupant protection. Therefore, a second priority was to assess advanced technology that would improve overall occupant system effectiveness.

First priority—reduce injury risk of air bags

Second priority—improve restraint system effectiveness

1.7 APPROACH

JPL constructed a series of tasks to meet the provisions of the NHTSA/NASA MOU and the objectives listed in para. 1.4. JPL is required to “understand and define critical parameters affecting air bag performance, evaluate air bag performance, establish the technological potential for improved (smart) air bag systems, identify new concepts for air bag systems and identify key expertise and technology within the agency (NASA) that can potentially contribute significantly to the improved effectiveness of air bags.” The following tasks were established to meet the provisions:

Assessment approach derived from the requirements of the NASA/NHTSA MOU

- (1) Critical parameters affecting air bag performance
- (2) Air bag deployment requirements
- (3) Air bag technology state of the art
- (4) Applicable NASA technology
- (5) Characterization of advanced air bag technology
- (6) Advanced air bag analysis and evaluation
- (7) Trends and strategies for advanced air bag system and technology development
- (8) Technology development recommendations

Early in the assessment it was determined that the effort required a fundamental engineering approach. Further, it was determined that real-world crash data were too limited to provide the analytical basis needed for an engineering assessment. Therefore, crash, sled and static test data and simulations, to the extent available to JPL, were the basis for engineering analysis and evaluation. These were augmented by supporting studies, where necessary, to obtain further insight or scaling factors.

1.8 REPORT READERS GUIDE

This report documents an assessment of the capability of advanced technology to make automobile air bags safer and more effective. The report sections contain the following information.

Section 2 is a very basic introduction to crash dynamics for those unacquainted with the subject. Readers experienced in the field may want to skip this section.

Section 3 describes the parameters that are basic to the analysis of air bag performance and to the assessment of improvements that could be made by air bags. The most important of these parameters, or critical parameters, are identified. They are the focus for evaluating advanced technology.

Section 4 discusses the requirements for advanced technology, and points out that these requirements are not readily available. Top-level requirements are established as a guide to the assessment.

Section 5 describes advanced air bag and safety belt technologies. This information was obtained from visits with automakers and restraint system suppliers, and from responses to a detailed survey questionnaire.

Section 6 summarizes a search within NASA for advanced technology that is applicable to air bags.

Section 7 provides an analysis of air bag performance and an assessment of advanced technologies. It describes the methodology adopted, which is based on the reduction of injury risk to occupants from deploying air bags by the application of advanced technology. The data available is used to develop sensitivities of the critical parameters. These sensitivities are applied to establish the improved safety of air bags by the introduction of advanced technology for future model year vehicles.

Section 8 provides a discussion of advanced technology development needs and factors involved in implementing the required development.

Sections 9 and 10 provide the conclusions and recommendations, respectively.

The appendices support special report topics for readers interested in the details of those topics.

SECTION 2—BACKGROUND

A crash typically occurs within little more than 100 milliseconds (ms). A determination to deploy air bags must be made in the first 20 ms or so in order to get them inflated within about 50 ms, or before an occupant has moved forward more than about 12 cm (5 inches). This timing ensures that the face of the bag has come nearly to rest before the occupant encounters it. A vehicle occupant actually continues at the original vehicle speed until he or she begins to be restrained by the air bag and/or safety belts. The occupant then becomes coupled with the occupant compartment and decelerates at a rate approaching that of the vehicle.

A simplified description of the vehicle and occupant kinematics is given in Figure 2-1 [17], which shows the velocity versus time for the vehicle and occupant. The crash occurs at time 0. The vehicle decelerates along the line AD with a deceleration of A_v , stopping at time D. The occupant continues at velocity A for time T until the restraint system takes effect at time B, when deceleration, A_D , occurs along the path BC. The area P represents the vehicle crush distance; the area S is the distance the occupant displaces before being restrained, and R is the distance displaced after being restrained.

Vehicle and occupant kinematics

Figure 2-2 shows a typical timeline for the deployment of a driver air bag and motion of a driver in a 48-km/h (30-mph) frontal collision into a barrier. This is the crash specified in FMVSS 208. The timeline begins when the front bumper contacts the barrier. The sensor obtains vehicle acceleration and velocity change data during the initial 15 to 20 ms of the crash and processes that data to determine if the crash pulse is likely to make air bag deployment desirable. (Some vehicles

Air bag deployment timeline

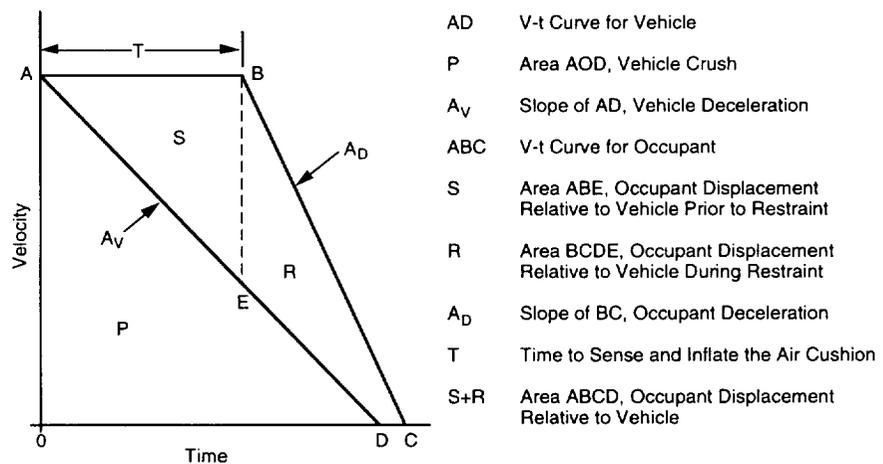


Figure 2-1. Simplified Kinematics

have multiple sensors with data processing in a central module, but we shall refer to such a combination as a sensor.) Once the sensor determines that the bag should be deployed, it sends an electrical signal to the inflator, where a typical inflation process energizes a squib to ignite its sodium azide pellets. As the sodium azide burns, it releases a copious amount of nitrogen that is filtered and cooled before entering the folded air bag.

As gas enters the bag, it forces its cover open at about 25 ms. This permits the bag to expand into the space between the steering wheel and the driver or between the instrument panel and the right front seat passenger. Within these first 25 ms, the occupant has continued to move forward at the original vehicle speed of 48 km/h (30 mph) while the vehicle has decelerated to around 40 km/h (25 mph). Because of the vehicle deceleration, the safety belt reel will lock and the occupants will move forward about 2 cm (less than one inch) in relation to the vehicle interior. The head, however, will continue to move forward after lockup.

By the time the bag is mostly inflated—typically just over 50 ms into the crash—the occupant will have moved about 10 cm farther forward in relation to the vehicle interior. If the occupant is belted, he or she will begin to load the safety belt during this time. Very shortly after that, the occupant and the face of the air bag come into contact. The bag (and belts if worn) then begin to restrain the occupant. Figure 2-3 shows the relationship between a belted driver and air bag within the decelerating frame of the vehicle at the three critical times during the crash. From this time forward, the occupant will be decelerated at about the same rate as the vehicle, which is on the order of 15 to 25 times the acceleration of gravity, until both come to rest at around 100 ms.

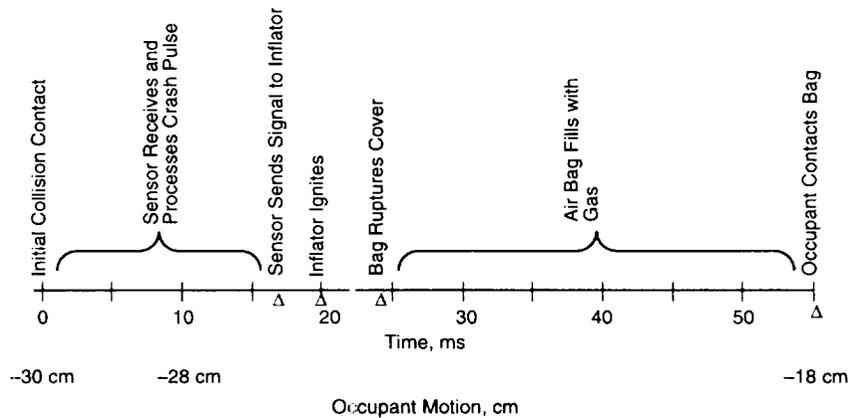


Figure 2-2. A Timeline of Air Bag Inflation and Occupant Motion Toward the Air Bag

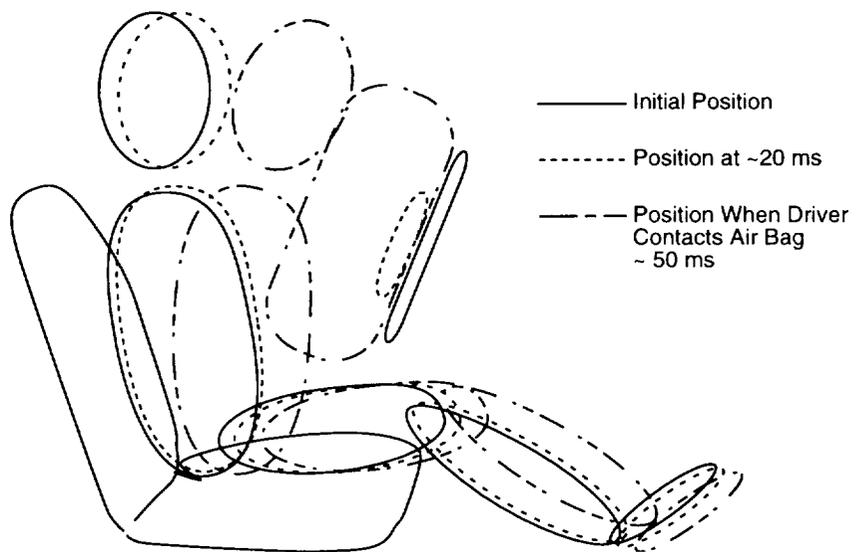


Figure 2-3. Driver Motion and Air Bag Inflation Early in the Crash

Occupant/air bag interaction

Figure 2-4 shows a time history of motion in a stationary frame of reference where the face of the driver at the beginning of the crash is the zero point on the position scale.

The vehicle is measured from the face of the steering wheel from which the air bag will emerge. Initially, everything is moving forward at 48 km/h (30 mph). As the vehicle decelerates from the crash forces, the air bag deploys, and its face actually moves rearward for about 25 ms at which time the occupant moves into it. The vehicle and occupant all come to rest over the next 50 ms or so. The velocity history of the vehicle, air bag and driver are shown in Figure 2-5.

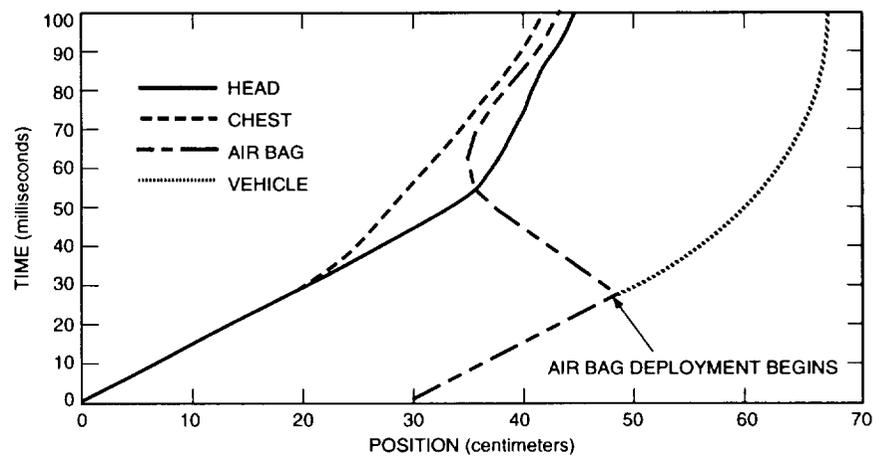


Figure 2-4. Driver Motion and Air Bag Inflation Early in the Crash in a Fixed Reference Frame

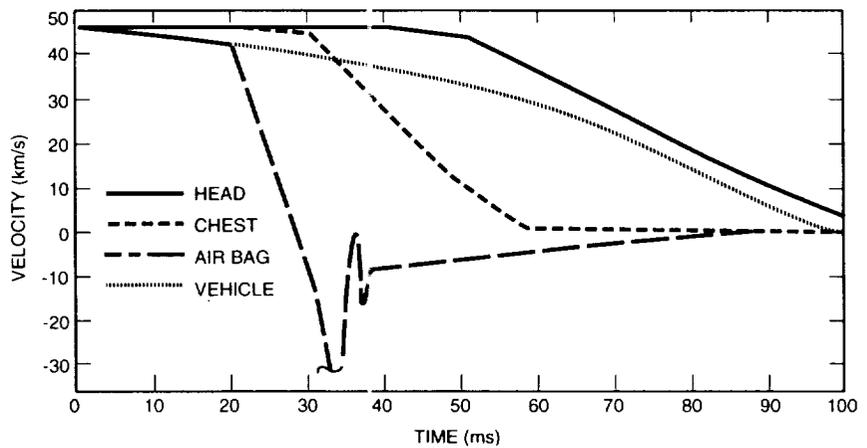


Figure 2-5. Time History of Velocity and Belted Occupant in a 48-km/h (30-mph) Crash with Air Bag Deployment

During a crash, an occupant gains velocity relative to the vehicle until restrained. The longer it takes to restrain an occupant, the larger will be the restraint decelerating forces. A quick-acting restraint is best to limit the loads on the occupant. Therefore, rapid deployment of the air bag is desired to limit deceleration loads as well as interaction during inflation with a normally seated occupant.

Figure 2-6 shows the velocity change and acceleration of small and large cars. Crash pulses can also vary considerably with the object impacted and the crash severity, i.e., the change in velocity, ΔV . The velocity and acceleration profile differences can be more dramatic than those shown in Figure 2-6, e.g., barrier-vs-pole crashes. (Note that Figures 2-4, 2-5, and 2-6 are illustrative of 48-km/h (30-mph) barrier crashes and do not reflect any specific crash or test.)

At the very bottom of Figure 2-6 is shown the air bag deployment timeline. Note how brief the time is and how little information is available when the air bag must be deployed. Thus, the timely prediction of crash severity is a very difficult problem, while it is critically important to the safe and effective deployment of the air bag.

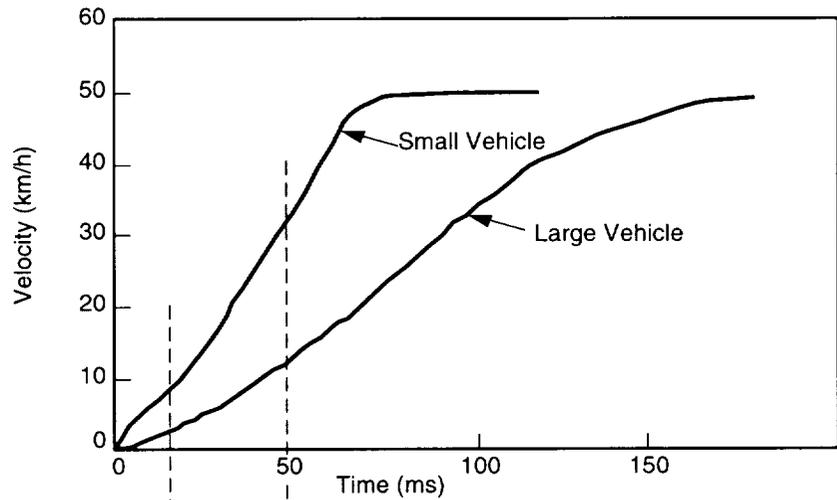
The air bag response is designed to protect the occupants based on a standard test, which is specified in Federal Motor Vehicle Safety Standard (FMVSS) 208. Until recently, the critical test was a 48-km/h (30-mph) vehicle crash into a fixed barrier that is perpendicular to the vehicle's line of travel with belted and unbelted 50th-percentile male dummies. The air bag must also be designed for barrier crashes up to 48 km/h (30 mph) and angles up to 30° in either direction from the perpendicular of the vehicle's line of travel. A recent temporary alternative to the barrier test for unbelted

Crash severity prediction required

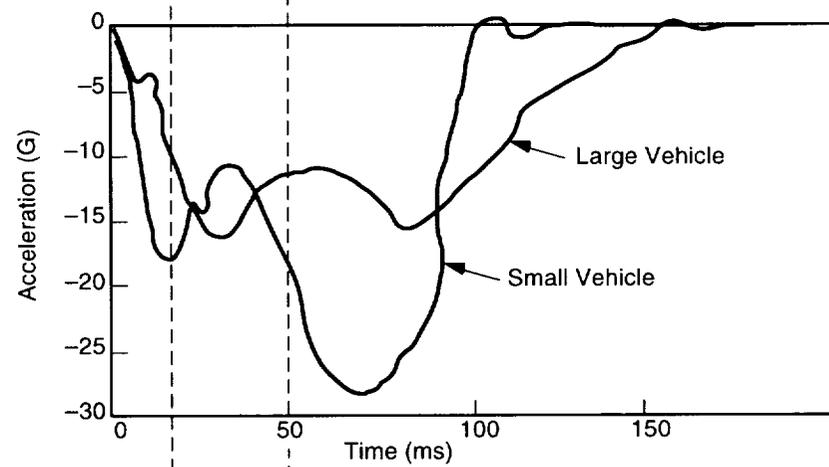
Regulatory testing

occupants, however, provides for a sled test with a prescribed 125-ms, 17.2-g half-sine pulse that will permit manufacturers to test vehicles on an expedited schedule with depowered air bags. The test uses 50th-percentile male dummies that represent an average male driver and passenger.

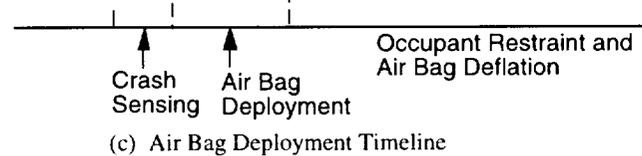
The automobile original equipment manufacturers (OEMs) conduct a wide range of tests to ensure that the air bags will not deploy under



(a) Crash Velocity Change ΔV , Range for 48-km/h (30-mph) Fixed Barrier Tests



(b) Acceleration Pulses, 48-km/h (30-mph) Fixed Barrier Tests



(c) Air Bag Deployment Timeline

Figure 2-6. Delta Velocity and Acceleration Pulses of a Typical Small and Large Car

Deployment/nondeployment testing

conditions not requiring an air bag, such as when traveling over rough roads or when involved in a fender-bender. These tests also ensure that deployment will occur under crash conditions requiring an air bag. As a result of these tests, deployment threshold velocities are established for each vehicle. They are typically 13 km/h (8 mph) for nondeployment and 22 km/h (14 mph) for deployment. Between these values is a “gray area” where the air bags may or may not deploy. OEMs and suppliers are attempting, through technical improvements, to reduce the gray area by raising the speed at which deployment begins to occur. There are types of crashes that pose special crash-sensing challenges, such as pole crashes and some types of offset crashes.

Extensive work in biomechanics supports the design of restraint systems. Studies of real-world crash data based on the Fatality Analysis Reporting System (FARS) and the National Automotive Sampling System (NASS) provide statistical information on fatalities and injuries. Injuries are ranked according to an Abbreviated Injury Scale (AIS), that varies from 0 to 6, where 0 is no injury and 6 is death. Intermediate rankings vary with injury severity, and each classification level has a list of representative injuries. Injuries are often classified as 2+, 3+, or 4+ to indicate a minimum level of severity for all injuries being considered.

Dummy tests are used to establish injury risk and air bag effectiveness

These AIS levels are related by the probability of injury risk to various injury criteria used in tests with dummies. The relationships have been developed from tests with cadavers, human volunteers, and, in the past, animals. The dummy injury criteria include head injury criteria (HIC); chest acceleration criteria in g's, chest deflection, etc.; several neck criteria; and femur loads. Acceptable injury criteria levels are established for dummy tests, where the test results indicate the severity of the test.

Air bags are typically tested in three modes: crash tests involving the whole vehicle, sled tests involving only the critical parts of the occupant compartment, and component tests or deployments in a static frame of reference. Dummies representing adults (50th-percentile males, 95th-percentile males, and 5th-percentile females) and children, provide measures of performance in these tests, with and without safety belts. These tests support assessment of the expected performance of air bags. Actual performance comes from real-world crash data.

Unfortunately, crashes typically are not neat, well-defined events such as the FMVSS 208 frontal barrier crash. Vehicles of different types

Large variation in crashes

(small and large cars, light trucks, vans) crash into a wide variety of other things (the fronts, sides and rears of other vehicles that also come in wide variety; poles; embankments; barriers; trees; and more). They do so at speeds that range from a non-damaging tap to a full-speed, demolishing crash, and at a variety of approach angles. The occupants who must be protected include people of all ages and both genders who range in weight from a few to well over 100 kilograms. They range in height from less than a meter to more than 2 meters. Although people usually sit normally in a seat, they also lean forward, recline their seat backs, put their feet on the instrument panel, or get into even stranger postures.

They may, or may not, be belted. In fact, the original impetus for the development of air bags (initiated by the auto industry, not the government) was the fact that fewer than one in eight Americans used safety belts. Air bags were originally thought to be an alternative to safety belts. Although virtually everyone in the field of auto safety now believes that air bags are best considered a supplement to safety belts, they are still designed, and must be tested, to protect unbelted occupants. The challenge of air bag design could be considerably simplified if they were only supposed to be a supplement to the protection of well-designed safety belts. Other countries that have high belt use, e.g., Australia and Canada, require air bag protection of belted occupants only. European countries are considering this requirement.

Cannot test for all crash conditions

Manufacturers test air bags in a wider set of circumstances than is required by FMVSS 208. They conduct offset tests, crashes at higher speeds, and other types of crashes and sled tests. Their tests are conducted using 5th-percentile female, 95th-percentile male, and child dummies in addition to the 50th-percentile male dummy. Nevertheless, they cannot possibly conduct tests that represent all possible crash and occupant conditions.

It is this daunting variety of conditions under which an air bag must perform that makes the job of designing safe and effective air bags so challenging. It is hardly surprising that the first generation of systems fell short of expectations.

Manufacturers and NHTSA have predicted that depowering will reduce the inflation-induced fatalities and injuries caused by air bags. The depowering improvements may come at the expense of large unrestrained occupants in severe crashes. It is not currently possible for a “one size fits all,” single-deployment-mode, air bag system to provide completely safe protection.

*Industry is developing
advanced technology*

As a consequence, OEMs and suppliers are developing advanced air bag components and systems to improve the variety and appropriateness of response to crash and occupant conditions. They are focusing on sensors to differentiate occupant weight, determine occupant proximity to the air bag module, improve crash severity predictions, and determine belt status, which will provide improved information about the crash and occupants. They are also working on two-stage inflators, a variety of air bag and module designs, and advanced safety belt concepts that will provide improved restraint response. The current restraint system state of the art and advanced technology options projected by industry are described in Section 5.

SECTION 3—CRITICAL PARAMETERS

3.1 INTRODUCTION

In the paragraph titled “Purpose of the NHTSA/NASA Memorandum of Understanding,” NASA is specifically charged to “understand and define critical parameters affecting air bag performance.” JPL first derived basic parameters to reflect the functions that may be required of advanced technology. We established them by reviewing the sequence of events of a crash and then classified them according to the information obtained about the crash and occupants and the response by the restraint system.

Basic parameters are described in Section 3.2 and shown in summary in Table 3-1. Certain of the basic parameters are more important than others in assessing the air bag system improvements that are possible with advanced technology. A review of the basic parameters led to a selection of the most important parameters, or critical parameters, which are discussed in Section 3.3 and shown in bold print in Table 3-1.

3.2 BASIC PARAMETERS

Basic parameters are those that describe both normal and off-design performance of current systems and improved performance from future systems using advanced technology. The functions of an occupant protection system were analyzed according to the total set of interactions that occur during a crash. These include interactions between the obstacle and the vehicle, the vehicle and the restraint, and the restraint and the occupant. This analysis assured that all major functions were accounted for.

The basic parameters were classified by the information provided about the crash and the occupants and the air bag system response. This classification was used throughout the study to analyze and assess the application of advanced technology.

For each function, parameters basic to the accomplishment of that function are listed. These parameters were established to fulfill the basic needs of each function. For example, in order to sense an object, its specific features and required discrimination accuracy must be specified. To detect motion, timing and accuracy of measurement are basic parameters.

Basic parameters derive from the need for information for air bag deployment and the need to provide a safe and protective response to that information

Table 3-1. Basic Parameters

Category and Function	Function Description	Basic Parameter
<i>Crash Information</i> Pre-crash*	Predict crash scenario and severity. Provide advanced crash information to ensure more rapid and appropriate air bag deployment and possibly pre-crash braking	<ul style="list-style-type: none"> - Obstacle type - Distance from vehicle - Closing velocity - Velocity vector - Discrimination accuracy - Reliability
Crash Severity	Predict crash severity from analysis of initial crash pulse	<ul style="list-style-type: none"> - Delta V - Crash pulse shape and variability - Threshold velocity/acceleration - Velocity vector - Time to deployment decision - Response time/accuracy - Reliability
<i>Occupant Information</i> Occupant Characteristics*	Determination of passenger and driver characteristics relevant to air bag use	<ul style="list-style-type: none"> - Front seat passenger presence (including whether the passenger is a child in a child safety seat) - Driver and front seat passenger characteristics (weight, size, age, gender . . .) - Discrimination accuracy - Reliability
Proximity*	Determination of occupant's actual or potential proximity to the air bag module	<ul style="list-style-type: none"> - Distance of each occupant from air bag module - Occupant velocity toward the air bag module - Accuracy of the determination - Time to update determination - Reliability
Safety Belt Status*	Determine safety belt use	<ul style="list-style-type: none"> - Detection of belt use - Detection of proper use - Discrimination accuracy - Extent of spool-out - Reliability

*Not currently part of most production vehicles.

Note: Bold print indicates critical parameter.

Table 3-1. Basic Parameters (Continued)

Category and Function	Function Description	Basic Parameter
<i>System Response</i> Control System & Deployment Logic	Computation to determine whether to deploy (air bag or pretensioners) based on processing of sensor input data concerning the crash pulse, occupant category, occupant proximity and belt status	<ul style="list-style-type: none"> - Speed of computation - Validity of decision - Reliability
Diagnostics	Determine system readiness by measuring subsystem functions	<ul style="list-style-type: none"> - Validity of determination - Reliability
Communication	Wiring of sensors, processors, and restraint system	<ul style="list-style-type: none"> - Speed - Reliability
Inflator Response	Inflator generates or releases, cools and filters gas for the air bag	<ul style="list-style-type: none"> - Ignition time - Inflation time - Gas mass flow rate, peak pressure and rise rate - Gas mass flow rate variability - Gas mass flow rate controllability - Reliability
Air Bag Response	Air bag moves into place and applies a decelerating force to occupant as a function of crash delta V, occupant weight (size), proximity to air bag, belt use, inflator and air bag design	<ul style="list-style-type: none"> - Deployment time - Cover design - Air bag design, folding patterns, chambering, venting design - Fabric weight - Air bag pressure - Air bag force vs time - Reliability
Safety Belt System	Occupant position control and deceleration during a crash	<ul style="list-style-type: none"> - Belt geometry & slack (including integration of belts with seats and adjustable anchorage points) - Elongation (stretch, spooling) - Pretensioning (response time, force and variability) - Load limiting (load levels) - Reliability

There are also a few parameters that are not derived from a functional analysis of the air bag system, but are important to the implementation of advanced air bag technology. Included in this category are cost, development time, and customer acceptance.

Some of the basic parameters are more important than others. For the purpose of this assessment a limited set of parameters that are considered to be the most important have been selected. These “critical” parameters are discussed in the following section.

3.3 CRITICAL PARAMETERS

We have defined a subset of the basic parameters that are fundamental to air bag operation. We call them the “critical parameters.” In our evaluation (Section 7) we have established the parametric sensitivities of the critical parameters and used them to evaluate advanced restraint technologies. The critical parameters are highlighted in Table 3.1.

Critical parameters are the most important parameters and are the basis for the evaluation

3.3.1 Crash Severity (ΔV and Crash Pulse). The crash type and the severity define what protective response is appropriate. These parameters include the range of crash types and severities that must be measured in order to determine the appropriate restraint system response. They describe the total change in velocity (ΔV , a vector quantity) during the crash, the peak acceleration (also a vector quantity), and some indication of crash type.

Crash severity

3.3.2 Belt Use Status. Belt use affects the job the air bag will have to do because the belts take a substantial part of the force of the decelerating occupant. As an example, Mercedes-Benz raises the minimum air bag inflation velocity if an occupant is belted.

Belt use

3.3.3 Occupant Weight, Size, Age, and Gender. The occupant’s weight and size are the most important of these, but since air bags are tested with various dummies, the simplest set of values for these parameters matches the dummies of a 6-year-old child, a 5th-percentile female, a 50th-percentile male, and a 95th-percentile male. The existence of an infant in an infant restraint, or a small child in a child safety seat, is a separate matter because these are likely to be sensed using a different mechanism. Age relates to size (children) and fragility (elderlyness) of occupants. Gender is a critical parameter in evaluating occupant injury risk because gender establishes the occupants’ fragility or likelihood of being injured by a given force or load that results from a crash. The fact that females are more susceptible to neck injury than males is reflected by the use of different neck injury risk curves for females and males.

Occupant categories based on test dummies

Proximity

3.3.4 Proximity of the Occupant to the Air Bag Module. This parameter describes the necessary conditions for inflation-induced occupant injury. For example, an occupant can be injured by an air bag only if he or she is in the path of the deploying air bag.

Deployment time

3.3.5 Deployment Time Including the Time to Sense the Need for Deployment. The timing of air bag deployment is important because frontal crash forces can move an occupant into the path of a deploying air bag if that deployment is delayed. For some types of crashes and crash sensing systems, this can put an unbelted occupant (and even some belted occupants) at severe risk. This parameter depends on timing, from the onset of the crash, of the following: crash sensor response, inflator ignition, and air bag deployment. This parameter is complicated by variability in air bag component performance that is not related to crash type or severity.

Inflator parameters

3.3.6 Inflator Response Parameters. Manufacturers are reducing the aggressiveness of air bag inflation by reducing the amount of gas-generating propellant in the inflators (depowering). This reduces the adverse effect of air bags, but may also compromise the ultimate protectiveness of air bags in high-speed crashes, particularly with very large occupants. The inflator mass flow rate is the most important inflator parameter.

Air bag design

3.3.7 Air Bag Response. The design, folding, venting, deployment path, cover design, and material of the bag determine how it will respond when inflated.

Reliability

3.3.8 Reliability. The ability of an air bag to respond when needed is fundamentally dependent on the reliability of all of its components. Reliability also affects whether an air bag will inflate when inflation is not appropriate (in the absence of a crash or in a crash where frontal crash forces are not great).

Although there are other critical parameters, the ones discussed above are considered to be the most important for the evaluation process, which was aimed primarily at the reduction of air-bag-induced injuries. In summary, the critical parameters are:

- Crash severity (ΔV and crash pulse)
- Belt use status
- Occupant weight, size, age, and gender
- Proximity of the occupant to the air bag module

- Deployment time, including time to determine whether to deploy the bag and the time to deploy the bag
- Inflator mass flow rate
- Air bag design
- Reliability

SECTION 4—REQUIREMENTS

OEMs establish requirements within the constraints of FMVSS 208

The process of developing advanced restraint technology is principally governed by NHTSA, the OEMs, and the suppliers. NHTSA establishes minimum safety levels through the federal motor vehicle safety standards (FMVSS 208, 209, and 210). The agency also influences development through its research and development, its consumer information program [the New Car Assessment Program 56-km/h (35-mph) crash tests], and public persuasion. The OEMs and suppliers work together to develop the systems that will meet federal standards, customer needs and expectations, and their own internal criteria.

Requirements for air bag advanced technology are not publicly available

The majority of advanced restraint development is conducted by the suppliers in response to specifications and requirements established by the OEMs. The OEMs are increasingly looking to the suppliers for more complete system development. Because of the competitive nature of the industry, its standards, goals, measures, and requirements for advanced technology to improve field performance have not been made public. The industry has made no public statements on what specific trade-offs it deems to be acceptable for the overall performance of restraint systems in the short or long term. A lack of clear objectives hinders restraint technology development. Without clear goals, system-level requirements can vary from OEM to OEM, and subsystem performance can vary among suppliers.

The suppliers that JPL contacted did not define or justify specific performance requirements for advanced technology. In most cases they deferred to the OEMs, but noted that OEMs had not provided requirements. Suppliers have been reluctant to define requirements on their own. The OEMs have established some subsystem requirements, such as for occupant weight sensing and child seat sensing. However, the requirements made available to JPL were insufficiently comprehensive to guide serious advanced system development.

JPL had to independently establish high-level requirements

Some OEMs that have been working on advanced technology for several years probably have established internal requirements, but these were not provided to JPL. To conduct the assessment of advanced technology, JPL established a candidate set of high-level requirements for the critical parameters in order to evaluate advanced technology. This is not a complete or comprehensive set of requirements, but these are what we believe are the most critical requirements for assessing the application of advanced technology.

Requirements categorized by information and response

In setting requirements, the air bag system can be divided into two parts: information and response. The information is provided by sensors that may measure crash severity, belt status, occupant category, and occupant proximity to the air bag module. The response is provided by the control system, inflator, air bag, and belt system.

An ideal restraint system would have complete and accurate information and an appropriate response. This provides a starting point for establishing requirements. A system with less than perfect information and responses would have to be relatively insensitive to variations from the perfect conditions (robust). Therefore, requirements must be established that demand some robustness, since no system can be perfect. Requirements for the critical parameters are as follows.

4.1 INFORMATION

4.1.1 Crash Severity (Crash Pulse Shape and Change in Velocity). The system must predict the severity of the crash and signal a deployment when the severity is sufficient to seriously injure front seat occupants. Crash sensors typically measure the change of velocity over a time period, the immediate acceleration, the jerk, or a combination of these parameters established by the sensor algorithm.

In the past, manufacturers established target ΔV levels (that is, the total change in velocity in a crash) for definite deployment and nondeployment. These targets were based on crash injury data that indicated the threshold ΔV when serious injuries or fatalities began to occur and might be prevented by an air bag. A nondeployment level was also established within which significant injury was unlikely even for unbelted occupants. There was a gray area between the two levels where the system might deploy or might not.

The gray area

Because a significant number of injuries and fatalities have resulted from deployments in low-severity crashes, there is an effort to increase the nondeployment threshold and reduce the gray area. Advanced systems that use a belt status sensor offer the potential of raising the thresholds if it is known that an occupant is using a belt. Mercedes-Benz already manufactures a system in which the deployment threshold is increased for belted occupants.

Typical deployment threshold requirements with belt use information are:

Deployment and nondeployment ΔV thresholds

- For belted occupants: 29 km/h (18 mph)
- For unbelted occupants: 22 km/h (14 mph)

The nondeployment threshold is:

- For belted occupants: 22 km/h (14 mph)
- For unbelted occupants: 13 to 16 km/h (8 to 10 mph) (the trend is toward higher values and reduction of the gray zone)

These values are approximate and will vary with vehicle manufacturer and platform. OEMs also establish requirements for different crash pulse shapes, representing different types of crashes—e.g., fixed barrier crashes, deformable barrier crashes, pole crashes, etc. Manufacturers specify more detailed requirements depending on their analysis of crash protection needs and the capability of the crash sensor algorithm. The move to higher thresholds for belted occupants needs further evaluation. Preliminary work indicates that air bags might not deploy in some crashes where they would provide important occupant protection. In other crashes, deployment may be delayed because the sensor algorithm delays the deployment decision. The availability of multistage inflators will also lead to consideration of alternative thresholds.

For this assessment the variability in crash severity was found to be critical, since air bag systems must be robust for the range of crash severities. The present lack of robustness is exhibited by late deployments that permit an occupant to enter the keep-out zone and interact with a deploying air bag. Pole crashes and some types of offset crashes are examples where late deployments can occur. In these crashes deceleration of the vehicle is relatively low in the early part of the crash, but increases as major structural components or the engine are engaged. Thus, the requirement for crash severity sensing must also include a requirement for timely deployment when deployment is appropriate. Deployment time, which is discussed below, is one of the most critical parameters.

4.1.1.1 Precrash Sensing. An air bag should be deployed as early as possible when it is needed in a crash sequence. This reduces the potential for inflation-induced injuries and provides the maximum ride-down distance for dissipating occupant kinetic energy. Early air bag deployment requires early crash detection and discrimination. The actual crash severity must be *predicted* at a time when the kinematic parameters are very small and the system has relatively little data on the crash.

Precrash sensing may provide for earlier air bag deployment

A number of groups have proposed that precrash sensing of obstacles could improve safety in two ways. First, it would alert drivers to possible crashes so that they could take actions to avoid them. Second,

it would provide additional, early information to the electronic crash-sensing modules that would facilitate earlier, accurate detection of a severe crash. With this information, the module could initiate air bag deployment at a point earlier in the crash than would be possible with a crash severity sensor alone.

Sensing for crash avoidance has been the subject of much research, and such sensors are now used and are commercially available—e.g., Eaton/VORAD radar-based sensors. The technical challenge for precrash sensing is to provide sufficient accuracy (particularly an extremely low false positive frequency) to reduce crash discrimination times.

Precrash sensing requirements not available

JPL has not found a set of detailed requirements that are guiding the industry's current development programs. Specific discussions with technology developers indicate that the real requirements and, most importantly, details of how the sensor information would be applied, have not been determined. Because of this, an accurate, quantitative prediction of the efficacy of precrash sensing (in terms of reduction of injury risk) is not possible. Such an analysis would be a crucial step that should come prior to extensive development.

Need to measure closing speed and obstacle inertia

The basic physics of crashes indicates that the velocity vector and offset are required to predict crash severity. Information that a vehicle is approaching an obstacle at 48 km/h (30 mph) is not sufficient to predict a 48 km/h (30 mph) "barrier equivalent" crash severity, as the obstacle's inertia is unknown. The sensor must predict whether the obstacle is fixed and massive (e.g., a barrier) or light and movable (e.g., an empty refrigerator box), or somewhere in between. Most obstacles will be other vehicles, but some will be fixed. Note that a determination of the inertia of a fixed obstacle also will require an understanding of the attachment of that obstacle to the substructure. Roadside hardware may pose difficulties due to the breakaway feature. At this time there is no sensor that can determine obstacle inertia or mass remotely.

No sensor available to measure obstacle inertia

Two scenarios for use

There are two possible scenarios for using the precrash closing velocity information to reduce discrimination times for air bag deployment. A precrash sensor could determine that a vehicle is closing on a large obstacle at a high enough rate of speed that air bag deployment is likely to be desirable. This speed would be determined specifically for each vehicle, depending on data such as seat belt status and occupant position/type. From an operational standpoint, information on the obstacle closing velocity/size would be used to *reduce* the discrimination threshold.

Early deployment may be possible by sensing a large obstacle and its velocity with the precrash sensor and an early high acceleration and jerk with the crash sensor. It is envisioned that the precrash sensor would only supplement the crash sensing system; it would not be used as a stand-alone system for predicting crash severity.

The precrash sensor also could be used to *increase* a deployment threshold in a crash severity algorithm, based upon knowledge that there is no significant obstacle approaching. This might allow the crash severity sensor algorithm to be tuned to offer improved immunity from certain nondeploy signals (e.g., rough road, undercarriage strike, etc.) and would reduce the unintended deployments.

Resolution and accuracy

For the purpose of reducing air bag deployment times, resolution and accuracy of the measurement of closing distance are important parameters. Resolution refers to the size of the minimum detectable signal in some bandwidth, while accuracy refers to the absolute error associated with the measurement. The requirements for system performance will depend upon the extent to which precrash sensing information is used in the deployment decision-making process. Significant use of precrash information will push resolution/accuracy requirements (for closing velocity) to approach those of inertial crash sensors. Limited use of the information will relax these requirements.

Because of the large expected measurement range (e.g., 10 m) of these systems, the required response speed will likely be much less than for crash severity sensing. A simple rule of thumb would be that response time, τ , is

Response time requirement

$$\tau \leq d_m/v_v$$

where d_m is the maximum measurement range and v_v is the vehicle velocity relative to the obstacle. This time is expected to be greater than 0.1 second.

Accuracy of the measurement of obstacle mass (inertia) is also critical, and this accuracy must be maintained with a variety of obstacle types. For example, the composition of the obstacle (e.g., metallic or nonmetallic) must not seriously affect the determination of its mass. Also, a useful system should be able to ascertain the nature of the attachment of the obstacle. The measurement of obstacle mass is a very difficult requirement, and there is no known method to achieve it. Obstacle size must substitute for mass as a current requirement.

Risks associated with pre-crash sensor use need to be studied

The risks associated with an *increase* or *decrease* of air bag deployment thresholds are somewhat different. An incorrect *increase* of deployment threshold, based upon precrash sensor information, may put occupants at risk in accidents with crash severity just at or above current deployment thresholds [~ 22 -km/h (14-mph) barrier equivalent ΔV]. The incremental injury risk caused by this factor would have to be studied carefully to assess the magnitude of changes of threshold, the expected reliability of the precrash sensor system, and the frequency of accidents at this severity.

An incorrect *decrease* of deployment threshold would lead to a number of additional deployments in those situations in which crash sensor-predicted severity is just at or below the current nondeployment levels [~ 13 km/h (8 mph)]. The overall effect of these additional deployments would depend upon their frequency and the status of the occupant (e.g., type and position) at the time of deployment. If there were no separate capability for detecting out-of-position (OOP) occupants, for example, then the number of air-bag-induced injuries would increase in this case. The magnitude of this increase would depend upon the equivalent size of the deployment threshold shift, as well as the frequency of situations in which at-risk (i.e., OOP) occupants are in vehicles undergoing dynamic events that have crash sensor signals in this range.

Disruption of driver operation because of an unintended air bag deployment could also be a serious consequence. This could happen in the case of a vehicle traveling at high speed, closing upon a stationary low-mass obstacle. In this case, the vehicle-obstacle interaction would provide very little deceleration to the vehicle. Errors associated with the precrash sensing system could lead to a precrash prediction of a more serious accident than actually occurs. Use of this precrash information to reduce the crash sensor-based deployment threshold could cause unintended deployments at *high speed*. This would be a potentially dangerous situation as the driver might be prevented from avoiding additional obstacles. Many other potential scenarios would have to be addressed before engineers seriously consider advocating precrash sensor technology for air bag deployment. JPL is aware of very little detailed precrash sensor analysis that has been performed to date within the industry.

4.1.2 Belt Status. A belt status sensor must reliably detect belt use and nonuse. It also must be reliable under expected scenarios of belt misuse.

4.1.3 Occupant Category. The presence of both drivers and front seat passengers must be detected with an accuracy that facilitates discrimination between the categories used for testing. It is unnecessary to discriminate beyond matching the capability of the restraint system to provide varying responses. Therefore, occupant sensors must detect or differentiate between:

Discrimination requirements of drivers and passengers

- Small, medium, and large drivers
- Children and small, medium, and large adult front seat passengers
- Child seating systems, and particularly RFCSs

Small, medium, and large adults correspond roughly to the currently available test dummies: 5th-percentile female, 50th-percentile male, and 95th-percentile male. Children are represented by 3- and 6-year-old dummies. The detector can use any method that will provide the required discrimination.

4.1.4 Occupant Proximity to the Air Bag Module. Proximity sensing has been proposed as a key component for an advanced air bag system that will eliminate inflation-induced injuries. In its simplest form, a proximity sensor could indicate that an occupant is dangerously close to an airbag module at the time a deployment decision is made. The application of a proximity sensor has led to the concept of a “keep-out zone,” which defines a dangerous zone around an air bag module when the air bag is deploying. Present concepts for advanced air bag systems use this zone in the following manner:

Keep-out zone

If an occupant is *inside* this zone at the air bag deployment decision time, then either *suppress* the air bag or deploy the bag at a depowered inflation level.

If *outside* this zone at the air bag deployment decision time, then, depending upon the status of other sensors, *deploy* the air bag.

The earliest application of proximity sensors could be in a quasi-static mode. The sensor could suppress or depower the air bag in response to a static OOP occupant. A static OOP occupant is one who is within the keep-out zone at the time of air bag deployment.

Quasistatic sensing

For full protection of occupants, dynamic proximity sensing is required. Dynamic occupant sensing determines the occupant who will move into the static keep-out zone during the air bag deployment, effectively enlarging the keep-out zone. The industry seems to believe

Dynamic sensing

that dynamic proximity information can improve the performance of advanced air bags by optimizing the restraint system for a wider range of occupant positions (beyond detecting static OOP occupants) and crash scenarios.

A discussion of the issues, and a list of initial requirements for proximity sensing systems, are included as Appendix C. The following is a summary of that discussion.

4.1.4.1 Dynamic Proximity Sensing Issues and Requirements.

JPL has investigated the application of dynamic proximity sensing to an unbelted occupant undergoing a generic AAMA crash pulse. Proximity sensing with a single keep-out zone shutoff boundary is problematical if this boundary coincides with the edge of the keep-out zone in front of the air bag. Occupants who are outside the zone at (or just before) deployment may move into the zone as the bag is deploying, putting them at risk of injury.

A decision zone larger than the keep-out zone is required because occupants move into the keep-out zone during a crash

Establishing a larger “decision zone” is one approach. The size of this decision zone depends critically upon the crash discrimination time. For some occupants, this zone may be larger than their initial distance from the instrument panel (IP) or steering wheel. In such cases, a proximity sensor could suppress the air bag in a large number of cases where it is desirable to provide crash protection.

A secondary conclusion from our kinematic analysis is that in current air bag-equipped vehicles without proximity sensors a large number of unrestrained occupants may be moving into the keep-out zone of deploying air bags in higher-speed crashes, in lower-speed crashes with precrash braking, and in multiple-crash events. Those occupants closest to the IP are at the greatest risk. Current air bag systems are likely to be injuring occupants in some of these crashes.

JPL has identified four important parameters: response time (position update time), resolution/accuracy (position accuracy), full-scale range resolution, and reliability.

Dynamic proximity sensing requirements

For the AAMA sled pulse, response times are expressed parametrically: 3 to 11 ms per cm of allowed error for crash discrimination time ranging from 40 to 21 ms (Appendix C). The allowed error depends on the occupant spatial tolerance to the deploying air bag.

Data on that tolerance is not available for either current or advanced air bags (which are intended to be more tolerant to occupant/air bag

interaction). At this time, we have specified requirements of a few milliseconds of response time and a few centimeters of accuracy. Further testing and analysis could support better specification of these values. The sensor must also be able to discriminate the occupant from other objects in the vehicle, such as maps, newspapers, or packages.

Full-scale range depends on a number of issues but is likely greater than 30 cm, based on the analysis presented in Appendix C.

Reliability estimates are covered in Section 4.2.4 of this report.

4.1.4.2 Quasistatic Proximity-Sensing Issues and Requirements.

Proximity sensing with low-update-rate sensors could improve static OOP occupant detection. The application of a sensor for this problem should avoid the response time problems of dynamic proximity sensing. Specifically, the response time, τ , should obey:

$$\tau_{\min} < \tau < \tau_{\max}$$

where: $\tau_{\min} \sim 21$ to 40 ms (a value that was determined by the desire not to affect dynamic performance)

and: $\tau_{\max} \approx 0.2$ to 2 s (a time small enough to permit detection of occupant-initiated motion into or out of a danger zone)

A full-scale range for a quasistatic proximity sensor can be smaller, as the intent is to measure only occupant intrusion into a smaller keep-out zone. This holds only for sensors mounted near the air bag module. The requirements for resolution and accuracy (including discrimination between occupants and other objects) and reliability remain the same as for dynamic proximity sensing.

4.2 RESPONSE

4.2.1 Deployment Time. Deployment time is one of the most critical parameters, because it relates directly to proximity of the occupant to the air bag. To be most effective in preventing occupant interaction with a deploying air bag, the bag should be deployed as rapidly as possible when it is appropriate for crash protection. The crash sensor must discriminate between events that require deployment and those that do not.

Quasistatic proximity sensing response time is less stringent than dynamic sensing

Need for rapid deployment

The current minimum air bag fill time is about 30 ms, so that a key to achieving rapid deployment is early crash-sensing. One guideline in air bag system development is the so-called “5 in. (13 cm) less 30 ms” rule. This rule, used by air bag developers, is that the occupant should not move more than 13 cm (5 in.) forward from the seat before the air bag is fully inflated. Thus, the time allowed for sensing crash severity is the time in which the occupant has moved forward 13 cm minus 30 ms (the time required for bag inflation). For a 48-km/h (30-mph) frontal barrier crash, this time for sensing is typically 15 to 20 ms.

Some moderate crashes can result in late deployments

For other crash scenarios, or for OOP occupants, the sensing time would be different. Crash severity sensing is well tuned to the 48-km/h (30-mph) rigid barrier test required in FMVSS 208. For other crash types, such as those into softer targets, the ability of the sensors to predict the crash severity and provide timely deployment of the air bag is compromised. This is particularly true when the crash is in the gray zone discussed above, which varies depending on sensor and logic. Work by a number of groups has shown that deformable offset barrier crashes of moderate severity often result in late deployments. In such crashes, belted 5th-percentile female occupants can be severely injured, while their injuries would not be serious without air bag deployment.

Maximum allowable deployment times

The crash severity sensors must provide early, accurate prediction of the crash severity. Reliable prediction is a particularly difficult sensing requirement. New algorithm developments are intended to improve the prediction capability of sensors. In setting requirements it is possible to develop parametric relationships that define the maximum allowable deployment times for different crash types and ΔV s. These parametric relationships will show trigger times of roughly 15 to 40 ms.

The system must deploy as rapidly as possible when an air bag is needed

The requirement, however, is always to deploy as rapidly as information to the sensor permits when an air bag is needed. This requirement applies also to the air bag deployment, and not only to the crash sensor. Manufacturers should consider air bag designs that can deploy more rapidly and deploy more safely in the effort to reduce deployment time. By deploying more rapidly, an air bag could be more aggressive, increasing the keep-out zone. If more rapid deployment is undertaken, designs to reduce harmful aggressiveness must also be introduced.

Achieving acceptable deployment times that are reliable and accurate for all crash scenarios requires a substantial test program. A major

AAMA sled pulse test is inadequate for deployment time testing

deficiency of performance testing with the AAMA sled pulse is that it does not test the performance of the crush zone or the crash severity sensors and algorithms. It is simply testing the performance of a subsystem in the total air bag system. The deployment time is specified to be early enough to avoid significant occupant interaction with the deploying air bag. It is important for the future to test the effectiveness of the complete system, including the performance of crash sensors and of any other sensors that are added to the system.

As a starting point, it would be possible to perform the AAMA sled pulse test on systems that rely solely on single-point sensing systems by using the system's sensor to trigger deployment. However, for crash severity sensing systems that employ crush zone sensors, this would not be possible. Ensuring that adequate deployment times will always be achieved would require an impracticably large testing program. The more extensive the testing can be, however, the more assurance a manufacturer will have that acceptable deployment times can be achieved under a broad spectrum of crashes.

4.2.2 Inflator Parameters. The system-level specifications for inflators are: ignition time, mass flow rate, mass flow rate variability, and mass flow rate controllability. The ignition time must be as short as possible, since any increase in air bag deployment time increases the probability of injury risk. Ignition times of current systems are on the order of 2 ms, so there is little opportunity for significant reduction. Further development should not focus on ignition time, unless necessary to ensure that ignition time does not lengthen significantly in cold weather. The mass flow rate and its variability and controllability are critical, however.

Ignition times are adequate

Analyses and tests available to JPL have not provided the optimal mass flow rate profile. A profile with a high initial rate results in lower chest injury risk when compared with alternatives. But a profile with a more gradual rise rate and lower peak pressure reduces neck injury risk. The performance of inflation with alternative profiles needs to be researched to determine the optimum profile for different crash pulses and occupants. This optimization process also needs to be performed for dual inflators.

Mass flow rate profile optimization needed

Today's pyrotechnic inflators have substantial unit-to-unit variability. Several sources have reported 3-sigma total variabilities of 25% to 30% at standard temperature. The variability increases over the operable temperature range. This variability is unacceptable for advanced systems that rely on dual- or multilevel inflation systems for a tailored response. The dual- or multilevel inflator response

Inflator variability is large and must be reduced for effective use of dual inflators

would be masked by such variability. The authors estimate that inflator variability must be 10% or less for each stage.

Inflator controllability is necessary for a tailored response. If detailed information about a crash and the occupants were available to determine inflation characteristics, an appropriate response would require an inflator with a highly variable mass flow rate and peak pressure. With the information that will actually be available in advanced systems, inflators with two or possibly three stages should be adequate. However, more controllable responses may be desirable, depending on the capability of the two or three stages to provide acceptable injury risk for all air bag/occupant interactions. Each stage must be capable of providing the appropriate response. The selected rise rates and peak pressures will have to be determined from the deployment strategies established for alternative crash scenarios. The authors cannot establish these requirements here.

Air bag design goal is to achieve a robust system

4.2.3 Air Bag Response. There are many new air bag designs that offer the potential of reducing injury risk for specific air bag/occupant interactions. They have the potential of more rapid and benign deployment via compartmented designs and other features. We cannot establish specific requirements for advanced designs. However, the general goal is to develop a robust system that will reduce deployment injuries while maintaining effective protection. The ultimate goal is that a deploying air bag should never cause injury. If that design goal could be achieved by air bag design alone, there would be no need for occupant and proximity sensors.

4.2.4 Reliability. The failure of an air bag to deploy when needed or an unintended air bag deployment can have serious consequences for automobile occupants. Air bag subsystem mechanical reliability limitations, in combination with a deployment algorithm, will determine the magnitude of both problems. An analysis is presented in Appendix D as the first step in an investigation of reliability requirements.

Using 1994 air bag deployment statistics, we have generated tables that show mechanical reliability and functional reliability for a driver-side air bag system as a function of unintended nondeployments and the ratio of intended to total deployments. Assuming that there are no more than one unintended nondeployment per year, and that the ratio of intended to total deployments is at least 0.999, then the average subsystem mechanical reliability must be 0.999995 (“5+ nines”) if subsystem mechanical failures are independent. For the system, the mechanical reliability will be 0.99998 (“4+ nines”) and the functional

reliability will be slightly less than 0.999. As the ratio of intended to total deployments increases, the mechanical reliability requirements increase for a constant number of unintended nondeployments.

System mechanical reliability requirement is nearly 5 nines; component reliabilities are higher

With expanded air bag installation (and deployments), a requirement of no more than one unintended nondeployment per year and at least 0.999 intended to total deployments implies an average subsystem mechanical reliability greater than 0.999995 and, at the system level, a mechanical reliability greater than 0.99998, with a functional reliability even closer to the ratio of 0.999 intended to total deployments.

System mechanical reliabilities of 4 to 5 nines are consistent with tens of unintended nondeployments and tens to hundreds of unintended deployments in the year 2000

Based on year 2000 projections for air bag installations and assuming 1994 deployment rates, approximately 262,000 deployments can be expected in the year 2000. If the system mechanical reliability is between 4 and 5 nines, with corresponding higher component reliabilities, and the number of unintended deployments is in the range 26 to 262 (0.01% to 0.1%), the number of unintended nondeployments consistent with those system mechanical reliabilities will be 2 for 5 nines and 21 for 4 nines. That result is insensitive to the number of unintended deployments within the stated range.

SECTION 5—OCCUPANT PROTECTION

ADVANCED TECHNOLOGY

5.1 CURRENT SAFETY RESTRAINT SYSTEMS

Safety restraint systems in current vehicles typically include seat belts and an air bag system. A block diagram of a typical safety restraint system is given in Figure 5-1.

Current system components

Current air bag systems include one or more crash sensors, a diagnostic and control module, wiring, inflators, and air bags. The inflators and air bags are packaged in modules that are under protective covers in the center of the steering wheel (for the driver) and on the right side of the instrument panel (for the center and right front passengers). The crash sensor obtains data from the forces of the crash. Those data are processed to determine whether air bag deployment is desirable for occupant crash protection. If the decision is to deploy the bags, an electrical signal is sent to the inflator to generate or release gas to inflate the air bags.

Safety belts

Production safety belts for outboard occupants are universally three-point systems consisting of a soft-edged belt that crosses the lap and then the chest from a lower inboard attachment point to the upper outboard attachment point. The upper outboard end of the belt usually goes through a “D” ring mounted on the “B” pillar of the vehicle and down to a spring-loaded reel. This reel permits the belt to feed out to fit occupants and their movements, but takes up slack in the belt. The reel has a device that locks it when forces on the vehicle indicate the need for belt restraint.

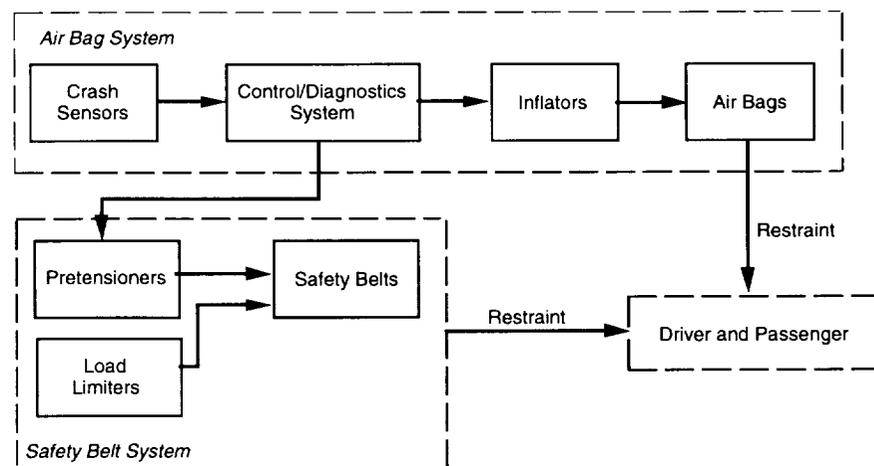


Figure 5-1. Schematic Diagram of Current Production Restraint System

Pretensioners and load limiters

Some safety belt systems have pretensioning devices that pull 10 cm or more of belt back into the reel to reduce slack and improve restraint performance. Pretensioners are triggered by crash sensors similar to those that trigger air bags. Some belts also have load-limiting devices that release belt webbing in a controlled manner to reduce peak forces on the occupant.

Automatic safety belts

For several years in the late 1980s and early 1990s, some manufacturers used automatic safety belts to meet the requirements of FMVSS 208. These systems typically moved a belt into place across the chest when the door was closed and had manual lap belts to complete belt protection. A few manufacturers used door-mounted manual lap/shoulder belts to meet FMVSS 208 under the pretext that these belts could be left buckled when the vehicle door was opened and closed, providing automatic protection. In fact, users of these vehicles almost never used the belts in this “automatic” mode. These belts often had poor geometry with outboard mounting points too far forward, permitting excessive occupant motion during a crash.

Electromechanical crash sensors

Crash sensors are all-mechanical switches, electromechanical switches, and/or electronic inertial sensors. Electromechanical switches are typically used in combinations of discriminating and safing sensors located at different points in the forward part of a vehicle. This is sometimes called multiple-point sensing. The discriminating sensors most often are highly damped electromechanical switches that activate at a specified change in velocity. These discriminating sensors typically are placed close to the front of the vehicle in the crush zone in order to provide information early in a crash. Low-threshold safing sensors are used to prevent unwanted air bag deployment from localized damage.

Single-point electronic sensing

A recent trend has been toward single-point or multipoint electronic sensing. In single-point sensing, an electronic accelerometer typically is placed in the occupant compartment. Its signal is processed by algorithms to determine crash severity. The intent is to make an early determination (from the forces transmitted to the occupant compartment), while maintaining immunity from signals that are not relevant to the need for occupant restraint. Electronic accelerometers are also used as multipoint sensors.

Air bag module mounting

The size and geometry of the frontal air bag modules are different for the driver and passenger. The driver-side unit must be packaged in the steering wheel. The passenger-side unit must be larger to accommodate a larger air bag and is packaged in the right side of the instrument panel. Different vehicles have alternative mounting

positions to improve air bag performance. In some vehicles, the passenger air bag is deployed in an upward direction to reduce loading on out-of-position passengers during deployment. Mounting of the side impact air bags is usually in the “B” pillars, doors, or the seat.

Inflators

Typical components of a current production inflator include an initiator, gas generator, filter/heat sink, and nozzle. The gas generator typically has only a single stage with fixed output. Traditional propellants are sodium azide or nitrocellulose. Hybrid gas generators using stored gas and a solid propellant heating element have recently been introduced in the passenger air bags of some vehicles. The filter/heat sink removes particulate matter and reduces the temperature of the output stream from the gas generator before it enters the air bag. The nozzle directs the inflator output stream into the air bag.

Air bags

Current air bags are usually made from multi-element sewn fabrics. The bag fabric is folded into the module housing. The type of fold used in the packaging of the air bag helps determine the bag geometry during the inflation process. Two schemes currently used are Petri-folding (P-folding) and Leporello-folding (L-folding). With the L-folding technique, the air bag is folded in accordion-type layers to a package that generally is located directly above the inflator. With the P-folding technique, the air bag is configured in the form of several concentric ring folds around the inflator. Tethers often are used to provide control of bag geometry during deployment. Vents control the release of gas from the air bag and permit the air bag to deflate after a crash. Current vents are fixed in size and remain open during the entire deployment.

Seat belts

The primary safety restraint system on current vehicles is seat belts. They include a three-point belt attachment with a single belt retractor and soft-edge webbing. The belt has a cable end-release buckle and free-running tongue. Specific belt designs vary considerably among current vehicles. Some new vehicles incorporate belt adjustment seat mounting, webbing grabbers, webbing elongation tailored to air bags, load-limiting devices, belt pretensioners, and belt sensors (to alter air bag deployment thresholds) into the seat belt system. Current belt pretensioners are low-output devices designed to eliminate belt slack during a crash event.

5.2 ADVANCED SAFETY RESTRAINT SYSTEMS

5.2.1 Introduction. Team members have had numerous technical exchanges with automobile manufacturers and system and component suppliers about technologies that may be used in advanced safety

restraint systems. The organizations contacted are listed in Appendix A. In addition, JPL distributed a questionnaire to all OEMs and suppliers who were known to be developing advanced air bag technology. The questionnaire is given in Appendix B.

*Reporting of technology
capability limited by
confidential information*

Most of the information received was confidential, including all data that supported performance claims. The advanced technology descriptions and capabilities presented here reflect the information and data gathered, but do not include details protected by the confidentiality agreements. Therefore, the descriptions do not include comparisons among competitors' systems or detailed descriptions of specific component capabilities. Instead, generic capabilities of technology type are presented. A summary of the technologies investigated and their characteristics is given in Table 5-1.

The technology survey and conclusions derived from it are based on contacts with a limited number of vehicle manufacturers and suppliers. The state of the art of advanced air bag technologies is in a high state of flux, and the technologies discussed in the report, as well as other technologies, may advance more or less rapidly than indicated in the report.

Based upon our discussions, we envision that future safety restraint systems may include advanced seat/seat belt systems, advanced inflatable restraints, and numerous sensors (for detection of precrash events, crash severity, occupant type/proximity, and safety belt status). These systems will need an advanced control system to monitor all of the sensor information and deploy selected elements of the safety restraint system (based upon an internal algorithm).

Future safety restraint systems

In an advanced safety restraint system, the control system will: (1) detect/determine crash severity from precrash and crash sensors; (2) detect position and size of occupants using data from a variety of occupant sensors and/or weight sensors; (3) detect belt use; (4) detect the presence of rear-facing infant seats (RFISs) and front-facing infant seats (FFISs); and (5) use the above data to modulate the performance of the variable portions of both the safety belt and air bag systems (e.g., fire pretensioners, enable low seat-belt load limits, turn off the air bag, etc.). This system may require more processing power than is available in current air bag control systems, as the system will process more data from multiple subsystems in a shorter time. A schematic diagram of an advanced safety restraint system containing all of these elements is given in Figure 5-2.

Table 5-1. Advanced Technology Characteristics

Technology Item	Technology Description and Function	Potential of Technology to Improve the Robustness and Performance of Safety Restraint System	Technology Maturity Readiness Date*
<i>Sensors</i> Pre-Crash Sensing	These sensors provide remote sensing (electromagnetic) for early crash severity determination.	The potential here is limited. The ability to determine obstacle inertia has not been determined. The implications of system unreliability are not defined, but they are potentially serious.	These sensors could be available for MY2001.
Crash Severity Sensors	These sensors are electromechanical switches and analog accelerometers for determination of crash severity.	Critical capabilities already have been demonstrated. A move toward analog accelerometers (single-point sensors) is underway. This reduces cost/complexity.	These sensors are available now.
Sensing Diagnostic Modules/Crash Algorithms	Improved algorithms are aimed at reducing discrimination times and unintended airbag deployments. Evolutionary design includes improved hardware compatible with an increased number of sensor inputs and restraint firing loops.	There is unclear potential for significant improvement. Details of current system performance are unavailable to JPL due to confidentiality concerns by companies.	Development here is ongoing.
Belt Use Sensors	These sensors determine whether or not a safety belt is being used.	Hall-type sensors have been developed.	These sensors could be available for introduction into vehicles by MY2000.
Belt spool-out sensors	These sensors aid in determining occupant size.	These sensors with seat position sensors could provide approximate information on occupant size and proximity, but JPL knows of no plan by industry for their use.	These sensors could be available by MY2001
Seat Position Sensors	These sensors could be used to estimate driver size and proximity to the air bag and passenger proximity.	These sensors would be a surrogate for occupant presence and proximity sensors, but would only provide approximate information.	These sensors could be available for MY2000.

* Technology readiness dates are those dates when production subsystems could be ready. Implementation into vehicles depends upon the OEMs' decision to include them and their technology deployment schedules, which could add one to three years to the model year readiness dates provided here.

Table 5-1. Advanced Technology Characteristics (Continued)

Technology Item	Technology Description and Function	Potential of Technology to Improve the Robustness and Performance of Safety Restraint System	Technology Maturity Readiness Date
<i>Sensors (cont.)</i> Occupant Classification Sensors	These sensors measure weight and presence for classification of at-risk occupants.	Weight sensors have fundamental inaccuracies and systemic errors. They have limited utility. Presence sensors show ability for occupant classifications. System reliability requirements are unclear. Child seat tags will provide the required performance. Required retrofit of existing child seats is an impediment.	MY2000 could see availability of weight sensors and presence sensors. Tags are available now.
Occupant Proximity Motion Sensors	These sensors involve remote sensing systems to provide range information between occupants and in-cabin hazards.	These sensors are useful for static OOP detection. The consequences of system unreliability are not well defined. Ultrasonic/IR systems hold the greatest promise. Utility of dynamic proximity information is not well understood at present.	These sensors could be available by MY2000/2001.
Computational Systems/ Algorithms	Such systems record all sensor signals to determine/actuate restraint system response.	These might replace upgraded crash sensor diagnostic modules, as systems requirements expand. Hardware currently is available. Utility of currently envisioned advanced algorithms has not been demonstrated.	These systems could be in use by MY2000.
<i>Inflators</i> Non-Azide Propellants	These materials replace sodium azide propellants to improve gas generant properties (i.e., they are smokeless and odorless, and they have fewer particulates and lower temperatures).	These propellants have lower temperature gas with no particulates. This will permit use of lighter-weight air bag fabrics, which improve performance. Simpler inflator designs are possible.	Some non-azide propellants are now used; however, they have higher gas temperatures. Low vulnerability (LOVA) propellants should be ready for MY2000.
Hybrid Inflators	These inflators use high-pressure stored gas in conjunction with a pyrotechnic charge.	These inflators have more desirable gas generant properties (i.e., fewer particulates). There is lower variability in performance.	More use is expected by MY1999. Units with LOVA propellants could be ready by MY2000.
Heated Gas Inflators	These inflators use a combustible mixture of dry air and hydrogen gas under high pressure.	The gas generant is clean and environmentally friendly. These inflators permit use of lighter-weight air bag fabrics to improve performance.	These units are expected to be ready by MY1999.

Table 5-1. Advanced Technology Characteristics (Continued)

Technology Item	Technology Description and Function	Potential of Technology to Improve the Robustness and Performance of Safety Restraint System	Technology Maturity Readiness Date
<i>Inflators (cont.)</i> Multistage Inflators	These systems use two separate inflators packaged as a single unit, or two separate pyrotechnic charges with a single inflator.	These inflators permit stages of air bag deployment depending on crash severity and occupant characteristics. Inflator performance variability could overshadow the potential advantages.	Two-stage inflators could be ready for production in 1998.
Inflators with Tailorable Mass Flow Rate	These systems provide control of inflator output in near real-time.	With appropriate sensor information, this technology would permit control of air bag deployment depending on crash severity and occupant location and characteristics.	These inflators are under development.
<i>Air Bags</i> New Fabrics and Coatings	Fabrics and coatings that are more flexible, lighter in weight and have lower permeability are now available.	These fabrics permit use of lower output inflators. Lower mass should reduce punchout forces on OOP occupants. These materials simplify bag folding techniques. Lighter-weight fabrics are less tolerant of particulates and high temperature gases.	Technology has been demonstrated with inflators having low particulates and lower gas temperatures. These materials could be incorporated with hybrid inflators for MY2000.
New Woven Fabrics and Bag Construction	These materials use controlled fabric porosity and improved weaving techniques to reduce or eliminate bag seams.	Fabrics having controlled porosity with low variability could eliminate the need for discrete vent holes.	This is an evolving technology, which could be incorporated as product improvement.
New Bag Shapes and Compartmented Bags	These alternatives involve air bags with multiple compartments, which inflate sequentially. Bags expand radially during deployment.	The first compartment can be pressurized much quicker to provide early occupant protection, with subsequent compartments maintaining the restraint force. This is especially beneficial to OOP occupants.	This technology could be ready for introduction in MY2000.
New Air Bag Venting Systems	These systems provide multilevel venting systems with discrete holes and continuously variable venting designs. Continuously variable venting designs would be controlled in near real-time based on available sensor information.	These systems provide pre-determined variation in venting depending on bag pressure. They provide rapid inflation of air bags (with no venting) to reduce occupant/air bag interaction. Continuously variable systems must be developed in conjunction with sensors and control strategies.	Multilevel systems could be available in MY1999. Continuously variable systems are being developed.

Table 5-1. Advanced Technology Characteristics (Continued)

Technology Item	Technology Description and Function	Potential of Technology to Improve the Robustness and Performance of Safety Restraint System	Technology Maturity Readiness Date
Seat Belt Systems Pretensioners	This technology involves high-output pretensioners to increase coupling between occupant and seat.	Maximizes ride-down distance for dissipation of the occupant's kinetic energy.	Pretensioners are in some vehicles now. Newer high-output devices could be ready in MY1999.
Load Limiting Devices	Single- or dual-level devices provide a fixed force level over the maximum occupant excursions. Continuously variable load limiters provide a wide variation of forces.	Dual-level load limiters can provide two-level selection based on knowledge of the occupant's characteristics. Further adjustability is provided by continuously variable devices.	Load limiters are in some vehicles now. Continuously variable devices could be ready in MY2000.
Inflatable Seat Belts	A portion of the standard three-point belt is inflated to augment the belt function.	These devices offer inflated cushioning and also provide some pretensioning of the seat belt. Air belts are less aggressive than air bags.	These devices could be ready by MY2001.

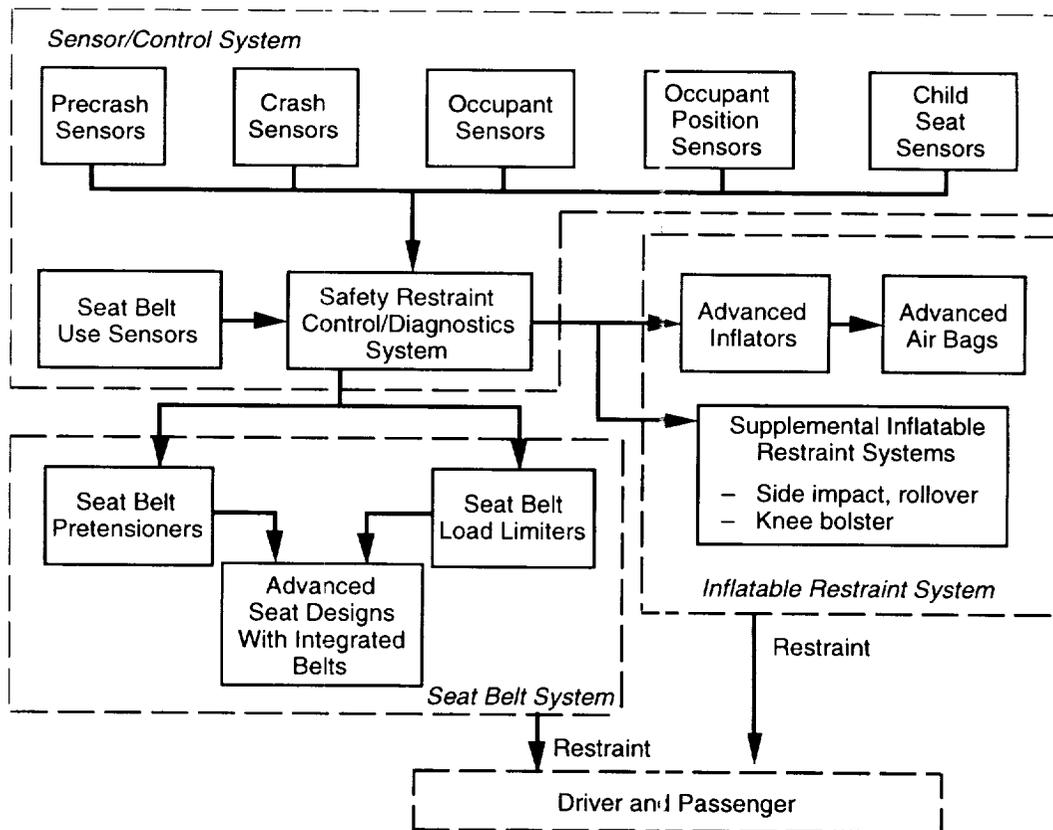


Figure 5-2. Advanced Safety Restraint System Schematic Diagram

5.2.2 Advanced Sensor Technology Development. Currently, the primary sensors in air bag systems are crash severity sensors. These sensors detect changes in the kinematic parameters (velocity and its derivatives) of the vehicle in response to a crash event and make a decision to deploy supplemental restraints (e.g., air bags) and/or enhanced primary restraints (e.g., seat belts with pretensioners). Many of the current limitations and liabilities of safety restraint systems are a result of insufficient crash and occupant information. Decisions by crash sensors to mitigate the hazards associated with very complex crash events are being made on the basis of a limited amount of data. Typically, only the first 15 to 20 ms of single-point crash sensor data (a time series with under 100 sample points) are used to discriminate between deployment and nondeployment events.

Limitations of current sensing: insufficient crash and occupant information

The general consensus in the industry is that restraint performance could be enhanced through the collection and use of other information. For example, restraint designers believe that a knowledge of the precrash environment, of occupant types/sizes and proximity to in-cabin hazards, and of the use of safety belts allow a restraint system response that is better tailored to the specifics of a given crash. In short, the view of restraint experts is that better crash information early in a crash can be used to generate a more appropriate response.

Need for more information is to be provided by new sensors

Additional sensors will be required to provide this enhanced information. The added sensors will enhance, but not replace, crash sensor information. Detection of an actual crash will remain a basic requirement for air bag deployment in the future.

Current advanced safety restraint sensor development is largely a process of evolution. Crash severity sensing technology began with multiple electromechanical switches, actuated at a specified vehicle velocity change [e.g., $V = 16 \text{ km/h}$ (10 mph)]. The current state of the art is analog accelerometers with data processing algorithms. These provide more accurate discrimination between crashes that do, or do not, require deployment. Ongoing refinements in crash-sensing systems are geared primarily toward “parameter pushing.” That is, evolutionary development provides incremental improvements to discrimination time values and immunity from extraneous information.

Some sensors will evolve; others require the application of new technology

A significant knowledge base exists from which advanced technology improvements can develop. Some advanced systems, however, will require the development and application of completely new technologies. The most active area of new technology development has been directed at elimination of inflation-induced injury (I^3) from

air bags. The primary focus has been on the detection of at-risk occupants in order to suppress air bag deployment. The industry is developing sensing technology to determine occupant characteristics and proximity to deploying air bags.

In the future the inherent speed of many proximity sensors should allow dynamic sensing of occupant proximity to in-cabin hazards. This capability should permit finer control of the response of the restraint system, which will improve the efficacy of the restraint system, in addition to mitigating its negative effects. To this end, precrash sensing has been proposed as a potentially important safety enhancement. Precrash sensing could provide both crash avoidance capability as well as earlier prediction of crash severity, which may allow earlier restraint system response. (Refer to Section 4.1.1.1.) In general, the requirements driving this new technology development are not as clearly understood, relative to crash sensors, because of the lack of critical field performance data.

Seat belt sensing technology is becoming more reliable. Thus we envision that seat belt status information will begin to play a role in the deployment of active restraints.

Advanced sensor categories

The advanced sensor technologies investigated by JPL are divided according to function. The categories are:

1. Precrash sensors
2. Crash severity sensors
3. Diagnostic modules and crash detection algorithms
4. Occupant size or mass sensors
5. Occupant proximity and motion sensors
6. Safety belt status sensors
7. Computational systems/algorithms

Precrash sensors provide advanced warning

5.2.2.1 Precrash Sensors. Precrash sensors could provide advanced warning of an obstacle. This information could facilitate crash avoidance or earlier air bag deployment. Information from the precrash sensor could prepare a crash severity sensor to make an earlier decision on whether or not to deploy the air bags. If an obstacle is seen by the precrash sensor with a high closing speed, the crash sensor could be programmed to deploy the bags as soon as major deceleration is measured. On the other hand, if no obstacle is observed by the precrash sensor before the crash sensor detects deceleration, the system may be programmed to require a higher level of deceleration or change of velocity before the air bags are deployed.

Pre-crash sensors are likely to be used first as part of a smart cruise control that adjusts the speed of the vehicle for traffic conditions. The industry is pursuing both radar and visible imaging technologies for pre-crash sensors.

Radar systems

One supplier's radar system uses dual antennas, operating as a phased array. Millimeter-wave pulses are transmitted into the region in front of the vehicle. Backscattered pulses are detected, with their travel time providing an indication of the range of the reflector. The received amplitude provides information on the size and composition of the reflecting object.

Another supplier utilizes a 1-mm² chip that contains all of the transmitter functions. The system is approximately 6×9×1.3 cm and fits under the front bumper. It senses an object within 3 meters and tracks speed and distance, thus providing distance and time-to-impact data to the crash recorder. It has been tested with many types of obstacles, road objects, and in various weather conditions.

The transmitted beam shape depends upon the application. Narrow beam shapes (high f-number optics) are used for automated cruise control, where long-range forward-looking capability and low-lateral interference are important. Short, wide beam shapes (low f-number optics) are used for pre-crash sensing. Here, sensing ranges of 0.5 m in front of the vehicle allow determination of closing velocity at least 100 ms prior to first impact. This provides sufficient early warning.

Sensor cannot resolve obstacle mass

The pre-crash radar system, through its data processing algorithm, can provide an indication of obstacle size by determining the solid angle subtended by the reflector. The ability to determine the inertia of the obstacle is not clear. No supplier could articulate any capability to resolve obstacle mass. The radar system consists of antennas/power electronics remotely located (at the front of the car) that interface with a separate electronic controller. It is not clear whether the controller's function could be implemented on the standard crash sensor/air bag controller system or whether a separate, dedicated system is required. One supplier quoted a cost for this system in the \$150–\$200 range, installed. Another said that it would be \$100 or less. Systems could be ready for introduction in MY 2001 cars if OEMs decided to do so immediately.

JPL's investigation found at least five pre-crash sensor development programs. Two suppliers provided detailed information.

5.2.2.2 Crash Severity Sensors. Crash sensors are physical transducers that convert variations in kinematic parameters (vehicle velocity and its derivatives) to an electrical signal. Two general types are in use: electromechanical switches that close an electrical contact at some specified signal level (typically the change in vehicle velocity) and analog sensors that provide an output voltage proportional to signal input (such as acceleration). Switches provide essentially a single response, while accelerometers provide a moderately large time series of data (a few hundred points) during a crash event.

Two types of crash sensors

Electromechanical switches typically are overdamped spring-mass systems that trigger after a specific change in vehicle velocity. Switches are placed in a number of areas, including the vehicle's frontal crush zone. In this way, the switch will trigger at a specified signal level, well in advance of that signal level being felt in the occupant compartment. The technology is mature. JPL's work uncovered no significant advanced development work in this area.

Electromechanical sensors

There was one new application of the technology worth mentioning, however. One developer reported a distributed crush switch to be located at the extreme front of the vehicle where it would provide early crash severity data over a wide angle. This system could detect narrow-object impacts and highly offset crashes that would not trigger the main crash sensor until later in the collision. Before the main crash sensor could detect the crash, the occupants might move into the keep-out zone. These sensors could work with the main crash sensor like precrash sensors

The size of the electromechanical sensors (a few cm³), although small, is an issue when compared to alternative technologies. One limitation, communicated by end users, was the difficulty in reliably raising the threshold of some present switch type sensors, because of limits to damping factors achievable with current geometries.

Analog accelerometers use a number of sensing technologies (piezoelectric crystals, silicon-based piezo-resistive, and variable capacitance) to develop extremely small (< cm³), low-cost sensors. The scale factor and full-scale range of the accelerometer can be adjusted easily during manufacture, and nearly all sensors have the capability for electrical self-testing. Because of this, accelerometers are seen to have advantages, especially from a systems perspective. At this time, accelerometer technology is fairly well developed. Further development is geared mainly toward price reduction and data processing.

Accelerometers

Electromechanical sensors are being replaced by single-point accelerometers

The trend is toward replacing distributed electromechanical crash sensors (switches) with single- (or dual-) axis accelerometers located in or around the passenger compartment. They are placed in areas that are likely to remain undeformed during a crash and that do not resonate during the crash. A common mounting is near the centerline of the vehicle behind the firewall on a structural component near the toe board where it is protected from the elements. Multiple crush-zone sensors are being replaced by a single analog accelerometer or single-point sensor. The rationale is three-fold: to reduce costs associated with multiple sensors and their installation, to improve reliability by minimizing wiring to areas vulnerable during a crash, and to improve the flexibility of the system. The latter point relates to the fact that an analog accelerometer provides a much larger volume of data with which to predict ultimate crash severity.

Processing of these data allows a prediction of severity on a time scale similar to that of a crush-zone-mounted switch, except for soft vehicle structures in narrow-object crashes, and possibly others. Deployment thresholds may be adjusted through software rather than the mechanical modification required for electromechanical switches. Placing the sensor in the occupant compartment simplifies installation (i.e., reduces its cost) compared to the crush-zone-mounted sensors. Because the sensor is situated in a *relatively* benign environment, there is less risk of malfunction of the sensor and its wiring. Although single-point sensing is becoming quite common, there are certain vehicle platforms that will still require multiple sensors. This is because of the inability of a single sensor to provide early crash detection for all crash scenarios.

Sensor performances are good, but the challenge is integration with the vehicle, which has a variable crash response

The strong consensus of the companies surveyed is that the performance of the sensor element itself is very good. The sensors provide accurate triggering (in the case of switches) and high-fidelity records of acceleration (in the case of analog accelerometers). The main challenges involve its physical placement on a particular vehicle and, most importantly, the processing of its data. Sensor placement is a critical step in the “tuning” process, where the vehicle crush characteristics over a wide range of crash pulses must be accounted for. This is critical for crush-zone switches.

5.2.2.3 Control Modules and Crash Detection Algorithms.

Advanced development of crash severity sensing systems is concentrating on digital algorithms for providing early, accurate restraint deployment decisions. These algorithms are applied to the data from analog accelerometers in single-point crash sensing systems. The analog signals (voltage vs. time) from the crash sensing

accelerometer are digitized by the module, typically at 8- to 10-bit resolution. The digital data are processed in real time, and the processed data are compared to a threshold to determine whether or not a restraint should be deployed.

Single-point sensing presents a challenging data processing problem

With single sensors mounted in the occupant compartment, this task involves determination of crash severity using a very small amount of low-amplitude data. For example, as shown in Appendix C for a representative AAMA crash pulse, a deployment decision must be made when the velocity of the occupant compartment has changed by only 3.4 km/h (2.1 mph). This can be compared to the approximate 16 km/h (10 mph) change in velocity seen at the same time by sensors (electromechanical switches) located in the vehicle crush zone. Although single-point analog accelerometer sensing is attractive from a systems standpoint, it presents a challenging data processing problem. A decision must be made at a point where the kinematic parameters are very small.

Suppliers are working on advanced algorithms for improved crash severity prediction

All developers are working toward the goal of providing timely decisions for a variety of crash pulses (including long duration events), while reducing the number of unwanted deployments. Most advanced approaches use either physical or pattern recognition algorithms (or combinations of both) to improve this determination. Physical algorithms attempt to calculate and evaluate physically relevant quantities (such as acceleration and jerk) that strongly correlate with crash severity. Pattern recognition techniques operate on the premise that particular crash events have unique signatures, and that these signatures can be used to discriminate crash severity. It was not clear to JPL which of these approaches is superior. All suppliers view their algorithms as valuable intellectual property, so it was not possible to get more than a cursory glance at any one approach.

The OEMs provide discrimination time requirements for each of a number of crash types [e.g., 48 km/h (30 mph) rigid fixed barrier (RFB), 40 km/h (25 mph) deformable offset barrier (DOB), pole]. Requirements are also provided for nondeployment in a variety of events [such as crashes with ΔV in the forward direction <14.4 km/h (9 mph), rough road driving, and undercarriage strikes]. The standard procedure for developing single-point crash algorithms is for the OEM customer to provide a set of acceleration data and required deployment times for various events (both deployment and nondeployment) for a given vehicle platform. The suppliers develop algorithms for processing these data to make proper deployment decisions with the required timing.

Some 7 to 12 types of different events must be considered, and often there are multiple data sets for each event, reflecting in part the observed variations in crash pulse. The algorithms must handle these variations consistently. Suppliers indicate that developing and testing these algorithms to handle this number of events is a large, time-consuming task. It is JPL's view that the extent of variation in real-world crashes is not fully accounted for in these developments.

Provision for crash variability is a challenge

As pointed out in Section 4.1.5, the recorded variability of crash discrimination times is large in some types of collisions with soft objects, such as the sides of cars. This may indicate that the current algorithms, while finely tuned for certain obvious crash pulses [e.g., 48 km/h (30 mph) RFB per FMVSS 208], may have limitations in some real-world crashes. An alternative viewpoint is that the observed deployment time variability in some events is due more to variability in the vehicle crush characteristics than to shortcomings in the algorithms. The vehicle crush variability results in variability in the signals recorded by the crash sensor.

In JPL's view, the current algorithm development process, relying on "representative" data sets, would benefit from the inclusion of this variability to a greater degree. One supplier articulated clearly that OEMs provide insufficient data to account for this variability. Providing these data is obviously a large and complex task. However, further improvements in crash severity sensing probably will require it. One supplier is attempting to include such variability into its system testing. In this case, random fluctuations are introduced into the high-frequency portion of the signals applied to a test thruster system.

The effects of this variability on the performance of the algorithm could be monitored during lab testing and subsequently minimized. This appears to be a good idea; however, an obvious future step would be to extend the technique to lower frequency in order to better simulate the effects of fluctuations in vehicle crush characteristics, for example. Still, the acknowledgment of the effects of these variabilities and the attempt to understand them is unique to this supplier. The importance of crash sensing to the overall performance of the restraint system makes it clear that any testing must include the crash sensor system. For example, compliance testing on sleds using generic crash pulses and a preset trigger time has limited value as it does not test the vehicle crush characteristics, the crash sensor system, or their interaction.

JPL discussed the development of advanced algorithms with six different suppliers. A consistent response to questions regarding their

Pole crash prediction is a problem

ability to provide timely crash discrimination for a range of crash pulses was that “we are able to meet the requirements of our customer.” The only unsolved problem mentioned by a subset of these suppliers was accurate determination of pole crashes. Here the obvious problem is an inability to detect this event, with its soft initial pulse, early enough to safely deploy the air bag. The suppliers provided very little data to support their performance claims. The data that were provided generally were the results from applying their particular algorithms to the typical data sets provided to them by their OEM customers. The extent to which the suppliers of crash sensing algorithms participate in actual crash testing is unclear. There is obviously some crash testing done by OEMs, but no supplier provided information on the variability in discrimination times observed in actual crash tests. The numbers they did provide appeared to be based on OEM-supplied data sets.

No field reliability data available

No supplier was able to provide specific reliability data for in-field performance. Real-world performance data from vehicle crashes are critical to understanding reliability in the field. The suppliers indicated that they do not have detailed numbers relating to field performance. At least one OEM, however, has investigated variability of deployment timing (see Section 4.2.1) observed in crash testing. The suppliers were not prepared to discuss the importance of field data.

Additional capabilities

Crash sensing modules are evolving to incorporate the requirements imposed by new restraint systems. This includes adding firing loops to control pretensioners, multistage inflators, and side impact air bag modules. Additional sensor inputs are being provided by suppliers to accommodate additional information from, for example, seat-belt sensors and occupant type/proximity sensors. Similarly, air bag deployment algorithms are being modified by suppliers (only slightly) to incorporate this information in order to provide the first types of “tailored response.” The technology is available to incorporate increased data processing required by future systems. The quality of crash sensor data and the methods by which the system response is determined are uncertain in current systems.

Future improvements in crash severity sensing systems will largely be evolutionary. A large number of single-point systems are currently in production vehicles. Introducing new performance features to existing products is a simpler process than introducing completely new systems. This is why improvements to crash sensing systems and their incorporation into vehicles will be a continuous process. Most suppliers indicated that these improvements add little additional cost.

Sensing occupant characteristics

5.2.2.4 Occupant Classification Sensors. Much of the advanced sensor development has concentrated on occupant detection. This includes classification of the occupant (size and/or weight) and the detection of specific cases (rear-facing or front-facing child seats, driver drowsiness, and so on). The initial use of this information is for air bag suppression or depowering to eliminate air bag-induced injuries. A more distant goal is to finely tailor the restraint system response to the specific characteristics of the occupant. For example, knowledge of occupant size or weight could allow different system responses for children, 5th-percentile females (5% F), 50th-percentile males (50% M), and 95th-percentile males (95% M).

Detecting occupant type is, by all accounts, a difficult task. It is made more difficult by the apparent lack of detailed performance requirements for the technology. Some OEMs have provided limited performance requirements related to occupant detection for air bag suppression. These include requirements for discrimination between rear-facing infant seats (RFISs) and normally seated adults, for example, but they stop short of providing detailed technical requirements on critical issues such as reliability. The lack of clear requirements is limiting technology development.

Four types of occupant classification sensors

Occupant classification sensing technologies fall into four main categories: (1) weight sensors, (2) presence sensors, (3) seat position and belt spool-out sensors, and (4) tag-based systems.

Causes of weight sensor inaccuracies

5.2.2.4.1 Weight Sensors. The purpose of weight sensors is to measure the mass of an occupant by measuring forces on the seat. In addition, some approaches measure weight distribution on the seat in order to improve the ability to classify occupants. There are many obvious limitations of a weight sensor approach, including the inherent inaccuracy of inferring mass and seating position from distributed seat forces. A weight sensor probably cannot account for the multitude of seating configurations for any one occupant. For example, the distribution of supporting forces between an occupant's upper torso (on the seat) and legs (on the floor) can lead to large inaccuracies. Additional forces (such as from seat belt tension) can also cause variability. Finally, tilting of the occupant (due to variable seat back angle) relative to the gravitational vector leads to inaccuracies.

Despite these limitations, the simplicity of a weight sensor, and the importance of knowledge of occupant mass, have led to a number of developments in this area. Mercedes-Benz offers a right front passenger seat sensor that shuts off the passenger air bag when the

seat is loaded at less than 30 kg, for example. NHTSA's consideration of an under-30-kg air bag suppression requirement also has spurred development.

Types of weight sensors

The majority of sensors use resistive strain gauges that provide a resistance change proportional to sensor strain. This strain is proportional to stress applied to the element, leading indirectly to a measurement of weight. Strain sensor technology is highly evolved: thick film sensors are available on flexible substrates, allowing integration into a wide range of structures. Separate sensors can be distributed over the same substrate in order to measure stress distributions. The technology is very durable and extremely cost effective.

A second sensor approach uses a monolithic pressure sensor to measure the load-dependent pressure increases within a sealed gas bag. In some cases, the strain sensors are placed near the seat surface, just below the trim, while in others they are placed deeper into the seat. Both placement locations obviously can be affected by elastic forces within the seat itself. In addition, either transducer type (strain sensor or pressure sensor) will have a finite contact area dependence. One proposed solution is to use similar strain transducers as load cells to measure the total force at rigid support points in the seat frame. In either case, incorporation of weight sensors may require modification to seat design, seat track design, and seat belt design in order to limit systemic measurement errors.

All suppliers contacted understood (and to a limited degree would communicate) the limitations of their technologies. A common caution was that the weight information "is used only to augment information from a suite of sensors. By providing even coarse weight information (i.e., small or large), we can improve the response of the smart restraint system." The problem with this view is that inaccurate information cannot realistically play a significant role in adjusting the restraint system response. No suppliers could provide useful numbers on system reliability for weight sensors. They provided no detailed performance data on resolution and accuracy.

Testing provided poor results

Some OEMs have performed comprehensive evaluations of various weight sensors relative to their use for air bag suppression. They performed a number of trials with a range of occupant types [(RFIS, FFIS, 6-year-old anthropomorphic test dummy (ATD) in booster seat and regular seat, 5% female ATD, 50% male ATD, and various live child and adult occupants)]. The objective was to measure the ability of weight sensor systems to classify these occupants. The tests were

done under static and driving conditions, both belted and unbelted, in a range of seat configurations. Their conclusion was that no system would provide a reasonable capability for classification. Particularly troubling was the common inability to distinguish between child seats and 5% females and to distinguish children. Live occupants presented classification problems for some systems. With some systems, there was a large degree of variability within occupant classes, large enough to cause overlaps between occupant categories. These generally poor results were enough to dissuade further extensive development by many suppliers.

Weight sensors are inherently inexpensive; however, integration costs may not be. Most suppliers indicated they could supply weight sensors for MY 2000 vehicles, which would require immediate implementation discussions with OEMs who currently view the technology as inadequate.

5.2.2.4.2 Presence Sensors. A wide variety of sensing technologies has been applied to the remote detection of occupant presence and type (e.g., RFIS). Each technology attempts to “image” an area in and around a seat and provide a classification of the occupant from this information. Technologies used include passive and active infrared, supersonic acoustic, capacitive (electric field), radar, and visible imaging. The primary development goal has been to detect and distinguish grossly at-risk occupants (e.g., RFISs) from normally seated adult passengers. It does not appear that classification of adult occupants by size has been a major performance goal.

Ultrasonic (acoustic) sensors are used in a number of systems. Acoustic pulses are transmitted from a set of 3 to 4 transducers. The transducers may be placed in the instrument panel, overhead console, and the trim around the A- and B-pillars. The pulses undergo reflections in the occupant compartment and are detected by the same transducer. Time-of-flight considerations limit system repetition rates to a few msec. Analysis of the echo signal, as a function of time, allows detection of the presence and range of multiple objects in the beam pattern. Multiple sensors provide the capability for classifying complex objects (e.g., RFIS) according to their echo patterns. Pattern recognition algorithms are used to generate these classifications.

Ultrasonic presence sensors

One clear limitation is that unintended reflectors (books, newspapers, body extremities, etc.) that approach close to the transducers will block the signal. In theory, the use of multiple transducers provides some relief from this. OEM tests of ultrasonic-only systems indicate that they are very effective (stated at 100%) at static detection of an

occupant in the seat. The detection of RFISs/FFCSs has been less successful (reported to be 70–95%). The required performance levels are unclear at present.

Infrared presence sensors

Infrared (IR) systems use either passive imaging of thermal signals with detector arrays or active ranging using near-IR sources (LEDs) and detectors. By itself, thermal IR imaging provides information of human presence and motion, but it is not used extensively for classification. Active IR systems are capable of providing ranging information at high speed, and with multiple channels, generating target-specific patterns. Unfortunately, IR systems are easily blocked by passenger clothing and accessories and are sensitive to surface properties of the target. OEM tests of selected IR-only systems have shown success in detection of occupant presence (100%) and RFISs/FFCSs (90%).

Combined acoustic/IR presence sensing systems

More advanced approaches are attempting to combine ultrasonic and IR technologies. One leading supplier is relying on multichannel acoustic ranging coupled with IR imaging to improve detection efficiency. The fusing and interpretation of data from multiple sensors (a considerable data processing problem) is seen by many groups as the best way to provide reliable occupant detection, even under continuously varying conditions. Many of the numbers quoted above for RFIS detection involved fairly well-controlled experiments. The real difficulty occurs in detecting a wide variety of occupant types in the presence of real-world variations. Multiple sensor approaches appear to provide the best capability for handling this.

Capacitive presence sensors

The third primary technology is capacitive sensing. This technology type senses the dielectric loading of an oscillating electric field set up between sets of electrodes. A dielectric body (a human) changes the field distribution. This change can be detected in a number of ways—for example, through measurement of the variation in the displacement current between the fixed electrodes. In this manner, the impedance (or capacitance) of the object can be detected. The fixed electrodes can be placed in a number of locations (IP, steering wheel, headliner, or seat cushion/back). While primarily used to measure proximity, the approach can provide classification. One supplier uses a set of four electrodes in the seat. Through a multiplexing approach in which one electrode is used as a transmitter and another as a receiver, a set of eight separate capacitance measurements can be made, each representing a unique dielectric path through the object. Analysis of these data allows some characterization of occupant type. OEM tests have shown some utility

in detection of RFISs as well as good discrimination between small and large adult ATDs.

Expected production costs range from between \$25 and \$75 for this technology. The cost of integration is highly dependent on sensor location, however. Most suppliers indicate potential production readiness in MY 2000; actual model year implementation would be later and would be determined by OEM acceptance.

5.2.2.4.3 Seat Position and Belt Spool-out Sensors. Driver-side seat position sensors can provide some indication of the size of the driver. They offer a surrogate for more direct measurement of driver weight or size, compared with the weight and presence sensors discussed above. They could be less accurate, but could be available sooner than the other sensors. Only one supplier mentioned work on this type of sensor, and very little information about its design or performance was provided. Hall-type sensors would be one approach for providing seat position.

Belt spool-out sensors can provide some indication of both driver and right-front passenger size, if coupled with seat position sensors. Right-front passenger size determination would be less accurate than that of the driver size, because the passenger seat position could not be correlated with passenger size. No supplier mentioned this sensor type, and we have no information on the expected accuracy of measurement. We do not know if spool-out sensors would be accurate enough to determine if an occupant is out of position.

The use of these two sensors would, of course, be an improvement over the current system, which has no occupant sensors. JPL would require additional information and need to conduct further analysis to determine the potential of these two sensors.

5.2.2.4.4 Tag-Based Systems. Other approaches to the detection of specific at-risk occupants, such as those in RFIS, have been developed. These include magnetic and electromagnetic tags attached to the child seat, either during manufacture or as part of a retrofit. The detection of a tag causes automatic suppression of an air bag. This technology has received considerable scrutiny, especially in light of plans to install air bag cutoff switches in certain vehicles. The availability of automatic tag systems could alleviate the need for operator intervention (via a switch). This may reduce the effects of operator error in specific cases. A number of technologies have been developed for this purpose. Most systems include transmit–receive coils (antennas) located in the passenger seat. The child seat contains a

Tags for RFIS detection

specific tag that modulates the electromagnetic field generated by the transmitter. The modulated field is detected and analyzed. The tag is passive (unpowered).

Tags for RFIS detection may be sensitive to childseat placement

There are a range of tag technologies. Some carry a unique code that is used to modulate the field in a specific manner. This approach theoretically reduces the error rate associated with detection. Specifically, it reduces the likelihood that a spurious signal could disable the air bag when a child seat is not present. On the other hand, there is general concern by OEMs over sensitivities of these systems to placement of the child seats, and whether improper placement could cause the system not to recognize a seat. This appears to be significantly less of a problem than the detection/discrimination requirements of either the weight-based sensors or the presence sensors discussed above.

Retrofitting car seats with tags could be a problem

JPL was not provided any substantial information on these systems by suppliers. Most of the information was provided by the OEMs, and the impression received was that this technology is not currently being considered for application by OEMs. One negative aspect is the need to retrofit existing car seats with tags and the potential consequences of the failure to do so. Based on JPL's technical judgment, this technology would carry costs similar to capacitive presence sensors. Its readiness has been demonstrated in Europe (Mercedes-Benz currently offers such a system).

5.2.2.5 Occupant Proximity/Motion Sensors. Occupant proximity sensors are intended to detect occupant position relative to in-cabin hazards. The first application is for air bag suppression or attenuation for static out-of-position (OOP) occupants. This is to mitigate the air bag deployment dangers for those individuals who are in the keep-out zone at the time of the signal to deploy the air bag. This application has commanded the largest amount of technology development.

Application of proximity sensing

A longer-term goal is to use real-time position information to modulate restraint deployment in order to improve its performance. This could include air bag suppression/attenuation to mitigate air bag-induced injuries for dynamic OOP occupants (those who have moved forward due to vehicle decelerations prior to and early in the crash sequence). As described in Appendix C, the use of dynamic proximity information for modulation of a restraint is problematical, due to the finite time period for air bag inflation.

One simple, but important, piece of information that can be provided by a proximity sensor is the initial occupant position. Knowledge of

the initial position allows, for example, more precise determination of occupant kinematics, using only a single-point accelerometer. This approach would apply to those crash sensing algorithms that calculate and use unrestrained occupant displacement in crash discrimination. The proximity sensor data establish the initial occupant position, something a crash sensor cannot do.

Requirement information is lacking

Requirements for proximity sensors are lacking. No supplier was able to state what measurement range was required for static OOP sensing, nor was there any information provided regarding required resolution/accuracy for these measurements. As noted in Appendix C, these requirements are air bag/inflator-specific. This lack of data may indicate that the suppliers and OEMs have not investigated these parameters in detail. Neither provided much information on reliability requirements. Quantitative information on the effects of various failures was not provided in any detail by either the suppliers or the OEMs.

Quasistatic sensors could be implemented in the next 3 to 4 model years

To be fair, it is probably premature to expect a thorough understanding of dynamic proximity sensing requirements, as this is a future application of the technology. The short-term option is to implement quasistatic sensing within the next three to four years in order to better eliminate static OOP air-bag-induced injuries. Understanding the potential safety trade-offs associated with the proximity performance parameters will be critical as this technology nears production.

Proximity and presence sensing technologies are the same

Proximity sensor functions are derived from the same technology described above for presence detection. Technologies that provide range information (including passive and active infrared, supersonic acoustic, capacitive, radar, and visible imaging) can calculate occupant proximity to air bag modules. The main technologies under development by the suppliers use acoustic and active IR ranging and capacitive position detection. One important characteristic of any technology used for proximity sensing is the effective point of reference on the occupant. That is, does the sensor detect the position of the *surface* nearest to the sensor or does the technology have volume-dependent sensitivities?

The critical distance is the one between the air bag module and the *closest surface* on the occupant. Technologies that are volume sensitive could only indirectly determine this distance, using knowledge of the size (volume) of the occupant. Volume-sensitive technologies lead to an inherent inaccuracy. Acoustic and IR ranging are inherently surface sensitive. The disadvantage of these sensors is

that they can be blocked easily by thin objects in front of the occupant. Capacitive proximity sensors are not as easily blocked by such objects. However, their signals clearly depend on the volume of the occupant. Stated another way, the output voltage vs. nearest-surface distance for an analog capacitive detector may be strongly dependent on the volume of the dielectric object. Knowing the distance of the occupant's dielectric center to the IP or steering wheel is not sufficiently accurate. It is not clear that any mounting location could provide an accurate enough distance measurement. The basic problem of capacitive sensors may be mitigated through careful design of electrode geometry, but it must be addressed. The measurement limitations had not been seriously considered by many of the suppliers who are working with capacitive technology.

Visible imaging

Visible imaging has been explored by some groups as a potential technology for occupant ranging (proximity). The emergence of highly integrated, low-cost detector arrays, as well as higher-performance processors, has increased the applicability of this technology. One approach uses stereo imaging along with firmware-based algorithms for determining range information at each pixel in a composite image. State-of-the-art algorithms have enabled 100-ms update rates, potentially suitable for quasi-static proximity sensing. The resolution and accuracy of this approach is competitive with those listed above. Processing requirements and their cost are an obstacle at the present time. Image systems lend themselves readily to a number of other measurement tasks. It is envisioned by some groups that the same technology can be used for occupant classification and for precrash functions (potentially allowing for obstacle classification). This is a long-term opportunity, however. None of the technology observed in this area was ready for near-term (i.e., MY 2001) application.

Acoustic and infrared sensors hold the most immediate promise

Because of the position measurement limitation of capacitive sensors and the long-term prospects for visible imaging, it appears that acoustic and IR-based ranging systems hold the most promise for meeting short-term requirements for static proximity sensing. There are a number of suppliers developing these technologies. Most suppliers state that static systems would be ready for introduction in MY 2000 or 2001. Actual installation time depends on the OEM's decision to implement and the time to do so. Actual implementation would be two years later. Targeted costs are in the range of \$35-\$60 for either acoustic or IR-based systems. Installation costs will vary by platform.

Capacitive sensors have potential application in the longer term

Capacitive proximity sensors appear to have longer-term promise for reducing system costs because of their inherent simplicity. Suppliers of this technology see a readiness date of MY 2001.

Dynamic proximity sensing requires system-level investigation

All technology suppliers still face considerable development periods for implementation of *dynamic* proximity sensing in a useful form. Much of this development is unrelated to the actual sensor technology. It will have to be geared towards a systems-level understanding of the specific requirements and expected benefits and risks associated with the *use* of this dynamic information in the restraint system.

All of these technologies have demonstrated the required response speed for most dynamic applications (a few milliseconds; see Appendix C). The physical mechanism of position detection does not really limit any of these technologies, although acoustic ranging at very large occupant distances may be limited by travel-time delays. Similarly, signal processing system speed should not be an impediment, as the requirements are quite similar to those for crash severity sensing.

Hall effect safety belt sensors are available for implementation

5.2.2.6 Safety Belt Status Sensors. Advanced safety belt status sensors using magnetic Hall effect transducers have been developed to improve reliability. Contact switches are considered to be too unreliable. Most parties contacted were fairly positive about the potential and readiness of Hall effect safety belt use sensors.

Available control hardware is adequate

5.2.2.7 Computational Systems/Algorithms. In advanced systems, an electronic computer module will analyze multisensor inputs and will control restraint deployments according to a stored response matrix. It was JPL's intent to solicit information on what developments were under way to accommodate future system requirements. Our investigation has shown that, across suppliers, availability of control *hardware* is not an issue. Current microcontroller technology spans a wide portion of speed/capacity phase space.

Interestingly, many suppliers of crash sensing modules have worked at streamlining their systems to operate on the least expensive 8-bit systems. Higher capacity (16- and 32-bit) processors are readily available to handle future requirements. The lead times for these items do not impose a significant impediment.

Algorithms need further development

Advanced algorithms (software or firmware) are another issue. Nearly every full-product-line supplier and all OEMs articulated strategies for restraint deployment, based on data from their own specific set of physical sensors. There will be no difficulty in implementing the

strategies as proposed on a time scale consistent with that of the sensor technology. What appears to be lacking, however, is a detailed understanding of the effects of inaccuracy, unreliability, and variability in the system's components. This will require a good deal of testing in real crash scenarios. JPL was provided no information on system-level testing procedures from any OEM or supplier.

Advanced inflator characteristics

5.2.3 Inflators. Inflators are undergoing continual development to improve the gas characteristics for air bag operation. Desirable gas characteristics include smokeless and odorless operation, cooler gas temperatures, and gases free of particulates. These environmental concerns have led to the development of non-azide propellants for inflator gas generators. Although these new non-azide propellants do offer improvements in gas characteristics, some of the new non-azide propellants produce higher gas temperatures than the sodium azide propellants and still contain some particulates. The particulates and higher gas temperatures make them less desirable for application with some of the new lighter-weight bag fabrics. Newer propellants offering smokeless/odorless operation and cooler gas temperatures are under development. Current pyro-type inflators are being modified to permit their use in depowered air bags and for dual-stage operation. Depowered inflators are being used in some current vehicles for implementation of depowered air bags to reduce inflation-induced injuries.

Two-stage inflators

Two-stage inflators permit two stages of air bag deployment depending on the severity of the crash. In some designs, the two-stage inflators are actually two separate inflators packaged as a single unit. In other designs, a single inflator has two separate propellant charges, which can be ignited separately or at the same time. The implementation of two-stage inflators is accompanied with the safety issue of disposal of the inflator after a crash in which only one of the stages of the inflator is used. This issue was not specifically discussed with industry. Therefore, their countermeasures are not known by JPL. It is possible to provide automatic disarming of the second stage after a crash, but the unit still must be removed, and the second-stage propellant must be fired or removed. Responsibility for the disposal will need to be determined. Two-stage inflators will be ready for production phase-in during 1998 by at least five suppliers.

Hybrid inflators

Hybrid inflators with pyrotechnic-augmented stored gas, as well as heated gas inflators, are in various stages of development. In pyrotechnic-augmented stored gas inflators, the gas is stored in a pressure vessel at high pressure (e.g., 20 MPa) with the exit port blocked by a burst diaphragm. The pyrotechnic charge is ignited,

and the evolved gas mixes with the stored gas, causing the pressure in the vessel to increase until the burst diaphragm is ruptured and gases flow into the air bag. Hybrid inflators are being developed for both single-stage and dual-stage implementations. Some dual-stage designs will be ready for production in 1999. In some dual-stage designs, the pyrotechnic charge is divided between two separate chambers of stored gas. This design allows maximum flexibility in tailoring the inflator output for specific crash requirements. The two pyrotechnic charges can be used separately or together. In dual-stage operation, the second stage can be fired when it is determined that additional energy is required (e.g., 30 ms after the firing of the first stage). When the newer propellants are implemented with hybrid inflator designs, much more desirable gas characteristics are obtained than those obtained with current sodium azide inflators. Hybrid inflators also offer lower variability in performance than current sodium azide inflators.

Heated gas inflators

In heated gas inflators, a combustible mixture of dry air and hydrogen gas is stored in a pressure vessel under high pressure. An igniter ruptures the burst diaphragm and ignites the hydrogen-air mixture, producing nitrogen gas and water vapor. Heated gas inflators are clean and environmentally friendly, since no particulates or noxious gases are formed in the combustion process. Both single-stage and dual-stage versions of heated gas inflators are being developed. It is expected that production of heated gas inflators will begin in 1999.

Cold gas inflators

Another inflator type under development utilizes helium gas stored under high pressure. This cold gas inflator produces a low-temperature gas and is clean and environmentally friendly. The cold gas inflator incorporates a variable throttling valve which can be used to adjust the inflation rate depending on occupant characteristics. This type of inflator shows significantly lower variability than pyro-type inflators.

Development of controllable inflators

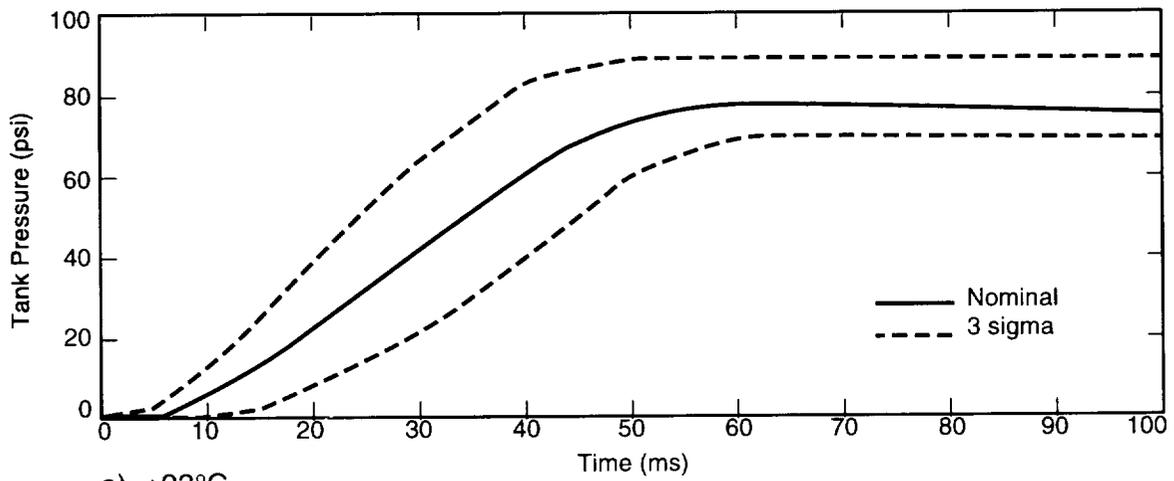
Operationally, the most significant change in future inflators will be the addition of the ability to tailor the inflator mass flow vs. time characteristics to optimize air bag deployment aggressivity and restraint force for different crash and occupant parameters. This control may be achieved through multiple staging of fixed mass flow stages or through continuously variable output inflator designs. Optimization of inflator design and operation to allow accurate variation of mass flow is an important area of current development. Near-term implementations will utilize inflators with several (two or more) fixed mass flow stages. Finally, technology is being developed to allow continuous variability of inflator mass flow in near real time.

This is a potential improvement over the quasi-static control of discrete stages.

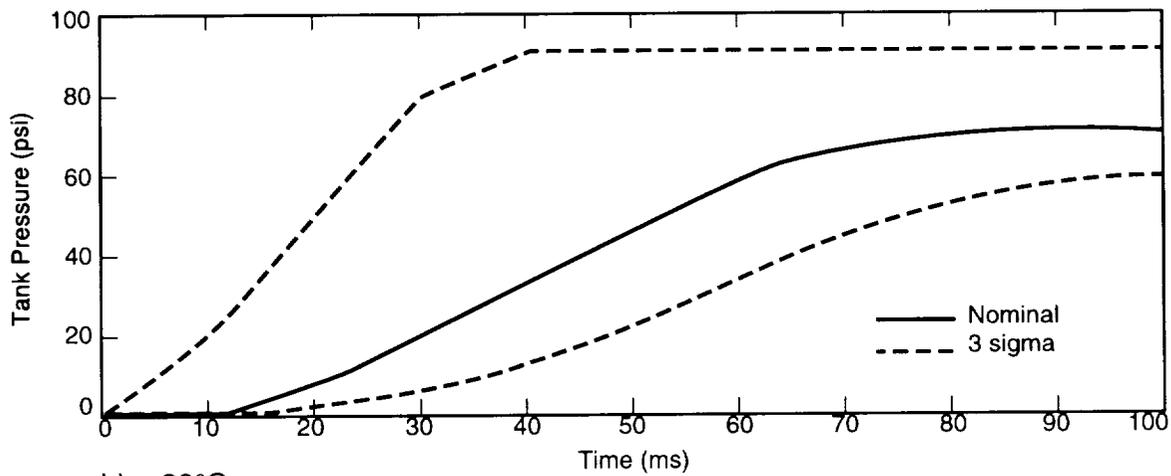
Inflator variability is a problem

An important consideration in establishing a deployment control strategy is inflator variability. Normally, inflators are characterized in constant volume tank tests by measuring the pressure-time history. Two parameters of importance in determining inflator performance are pressure rise rate and final pressure level. The two factors leading to inflator performance variability are ambient temperature and unit-to-unit manufacturing variability. For inflators using azide propellants, the maximum tank pressures show a variation of about 25% to 35% over the temperature range from -30°C to $+80^{\circ}\text{C}$. The temperature sensitivity of inflators with non-azide propellants is about one-half as large as that for azide propellants. Tank pressures measured early in the inflation process show a much larger variability with ambient temperatures. This is probably due to the dependence of ignition delay and burning rate on ambient temperature. Temperature variation is significant in terms of the time required to inflate the air bag. At cold temperatures, slower bag inflation could result in delayed deployment time and/or a significantly depowered air bag. Temperature control may be needed and is feasible. In principle, compensation for this temperature variability could be obtained by changing the venting rate as a function of ambient temperature and/or providing heating in cold temperature.

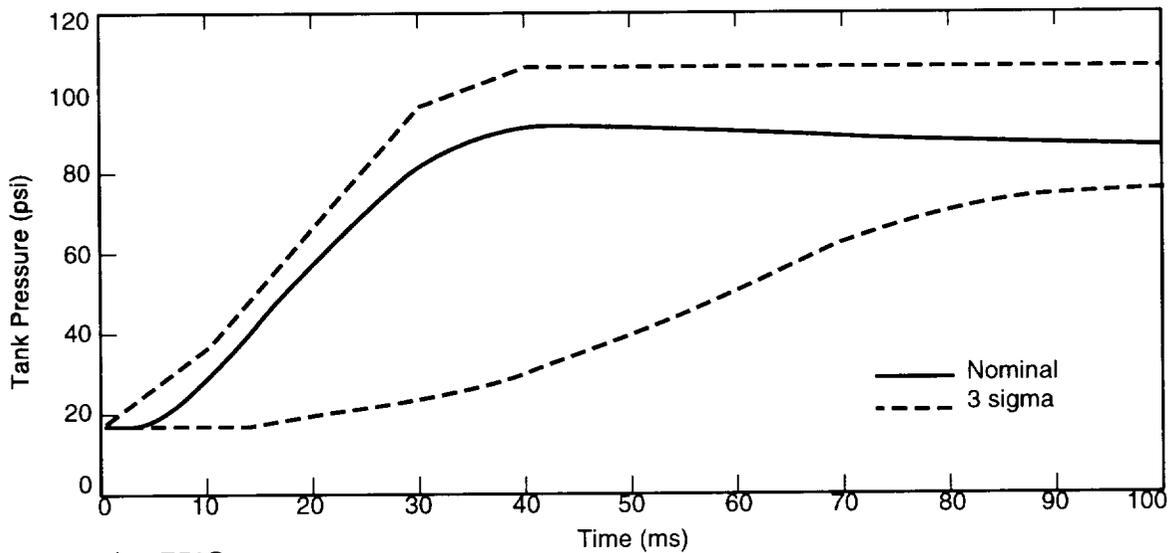
The unit-to-unit manufacturing variability is not easy to control. At ambient temperature, the performance variability of pyro-type inflators is due to a combination of factors, including performance of gas generant and igniter material, filter/heat sink materials, initiator, quantity of gas generant, and amount/geometry of igniter material used. For inflators using azide propellants, the unit-to-unit variation (one standard deviation) in maximum tank pressure is about $\pm 3\%$ at ambient temperature. The unit-to-unit variation of inflators with non-azide propellants is about one-half as large as that for azide propellants. The unit-to-unit variation (one standard deviation) in pressure rise rate is about $\pm 10\%$ for azide propellants and $\pm 6\%$ for non-azide propellants. Unit-to-unit and temperature variabilities for azide propellant systems are illustrated in Figure 5-3, which shows the nominal and 3-sigma variations for unit lots at these temperatures. The unit-to-unit variability and temperature sensitivity of current inflators are significant and could, in many cases, overshadow the potential advantages of implementing depowered or two-stage inflators.



a) +23°C



b) -29°C



c) +75°C

Figure 5-3. Three-Sigma Inflator Variables for Single Inflator Lots, i.e., Unit-to-Unit Variabilities as a Function of Temperature

Hybrid inflators and heated gas inflators show less unit-to-unit variability and less temperature sensitivity than do other inflator types. The maximum tank pressures for hybrid inflators show a variation of about 10% to 15% over the temperature range from -30°C to $+80^{\circ}\text{C}$. Tank pressures measured early in the inflation process show a much larger variability with ambient temperature. For hybrid inflators, the unit-to-unit variability (one standard deviation) in maximum tank pressure is about $\pm 1\%$ to $\pm 2\%$ at ambient temperature.

Better control of inflator variability is essential to enable implementation of control strategies for advanced safety restraint systems. Variability control must begin with the design, development, and production process. Temperature compensation may be required. Active, near-real-time control of inflator output could minimize the deleterious effects of inflator variability.

Advanced inflator costs

Relative to baseline single-stage pyro inflators with azide propellants, the projected added cost of advanced inflator types is \$10–\$15 for dual-pyro inflators, \$0–\$8 for hybrid and heated gas inflators, and potentially lower cost for high-pressure stored gas inflators.

Trend toward lighter-weight fabrics

5.2.4 Air Bags. Air bag developments are moving in the direction of thinner, more pliable fabrics, lighter coatings, and simplified sewing patterns. This trend is in part to reduce cost, but it is also the application of advanced technology. Factors which influence the choice of air bag fabric include packaging volume in the air bag module, strength requirements (based on the inflator aggressiveness), and thermal requirements (based on the gas exit temperature of the inflator). Several fabric manufacturers are developing lightweight, low-permeability air bag fabrics. The light weight and low permeability will permit the use of lower-output inflators, and that, in conjunction with the lower air bag mass, should result in lower punchout forces on out-of-position occupants. The lighter-weight fabrics will simplify bag folding techniques, possibly eliminating the need for tethers. However, these lighter-weight materials are generally less tolerant of particulates and high-temperature gases. Thus, these lighter bags must be used with inflators that have lower temperatures and minimum particulates.

Bag fabrication developments

There are some development efforts in weaving technology that have produced a one-piece bag. Efforts are being made to better control the processing of woven fabrics to minimize the variability in the porosity of air bags. The focus is to provide near-zero permeability of the fabric on the front panel (i.e., the panel contacting the occupant) and to provide known porosity of the fabric on the back panel for

controlled venting. Controlled air bag porosity, with low variability, could permit venting to be accomplished through the air bag fabric and eliminate the need for discrete vent holes. Other, nonwoven materials are being considered to simplify manufacturing.

New folding patterns

New folding patterns are being developed constantly, with the goal of reducing occupant interaction effects, especially for OOP occupants. One such folding pattern causes the air bag to expand radially during deployment, putting much less force against an OOP occupant. This folding pattern results in a reduced packing efficiency, making it a challenge to pack it into some new driver side air bag modules.

New tether designs also are also being developed. These new designs will permit earlier loading of the tether, thereby reducing the energy transmitted to an OOP occupant.

*Compartmented air bags
show promise*

New bag shapes and designs are being developed to reduce the loading of OOP occupants. Air bags with multiple compartments are being developed, the potential benefit being that the different chambers can be pressurized sequentially, in order to maintain sufficient restraint force. The first compartment can be pressurized much quicker than a full-sized bag to provide some early occupant protection. When the pressure in the first compartment reaches a predetermined level, a port into the second compartment (a tear strip or perforated port) opens to begin filling the second compartment at the predetermined pressure level. Air bag concepts with the compartments arranged axially and radially as well as bags within bags are under development. The bag-within-a-bag configuration was developed and demonstrated for 80 km/h (50 mph) occupant crash protection by Minicars, Inc. in the late 1970s and early 1980s. It showed good performance in tests by NHTSA. Compartmented air bag designs could be ready for production by the year 2000.

Venting

Air bag venting systems are designed to be used in conjunction with a combination of air bag volume, inflator performance, and desired venting characteristics. Suppliers are evaluating multilevel and continuously variable venting designs for use with future air bags. Used in conjunction with appropriate occupant sensors, these designs could control venting as a function of occupant type and position. Current venting is achieved through constant area vents that are continuously open and/or through porous bag material. Some venting designs under development utilize no venting during the initial bag-filling process until a predetermined bag pressure is achieved. At that time, a constant-area venting port opens to provide venting for

the remainder of the deployment event. The port (e.g., a tear strip or perforated port) is designed to open at a predetermined pressure level. This system will be in production in 1998. As with inflators, a longer-term goal of providing real-time, variable bag response has been put forward by several suppliers and OEMs.

JPL did not investigate some advanced developments

5.2.5 Future Supplemental Safety Restraint Development. In the future, more vehicles are likely to have additional supplemental restraint systems such as air bags for side impact, rollover, and knee bolster functions. Technologies to improve the performance of air bags and inflators continue to evolve. Suppliers are also studying potential improvements in air bag packaging techniques. JPL did not investigate these developments in depth.

Safety belt systems can be improved

5.2.6 Safety Belt Systems. Belt makers are developing several performance enhancing features for three-point seat belt systems. These include belts with high initial stiffness, high-output pretensioners, and variable load-limiting devices.

Pretensioners

High initial belt stiffness, coupled with high-output pretensioners, generates a high degree of coupling early in the crash between the occupant and the passenger compartment or seat. One benefit of this is to maximize the ride-down distance for dissipation of the occupant's kinetic energy. Higher belt stiffness is gained through the use of low-elongation webbing, short belt loops, rigidized belt anchorages, and new seat belt geometries (including four-point harnesses). Higher-output pretensioners also increase the initial stiffness of the primary restraint system. Providing this high force over longer stroke lengths is a key to improving occupant coupling to the seat for a wide range of initial occupant positions. To this end, longer stroke pretensioners are under development.

Load limiters

Variable load-limiting devices are tuned to provide a constant force level over the maximum occupant excursions. Present concepts use single and even dual levels (which are preset). Concepts exist for continuously variable load limiters, in which the force level could be adjusted by the control system based upon information about occupant mass and position provided by the system sensors.

Seat design

By initially coupling the occupant to the seat (e.g., with pretensioners), the capability exists for using or adjusting the mechanics of the seat itself to dissipate kinetic energy. This approach requires seat belts that are integrated with the seat as opposed to belts with attachment points on the vehicle pillars. Concepts have been developed for improving occupant energy management through tuning the initial

stiffness of the seat, controlling seat attachment forces, and integrating belts into the seats.

Air belts are a promising technology to be investigated further

Finally, seat belt designs with inflatable elements (air belts) are being developed. The inflatable element augments the standard three-point seat belt system by inflating the shoulder-belt portion of the belt during impact. In one concept, the fabric of the inflatable element decreases in length when inflated. Thus, the inflatable element also pretensions the seat belt. Air belts are likely to be less aggressive than air bags because they do not expand with great force toward the occupant.

At this time, no suppliers or OEMs are considering potentially more effective safety belt designs, such as four-point harnesses.

Studies have shown that systems that combine the implementation of advanced belts, pretensioners, load limiters, and air bags offer the potential for enhanced protection.

5.2.7 Manufacturing Considerations. Manufacturing, production quality control, and other related considerations, although important, were secondary issues relative to performance in this assessment. A detailed evaluation of manufacturing issues was beyond the scope of this assessment. Manufacturing issues affect the technology costs and availabilities. None of the suppliers mentioned manufacturing differences between technologies as significant factors, other than their effect on cost and availability. Manufacturing considerations are imbedded in these values. Some suppliers have indicated that manufacturing requirements will lead to phased implementation of advanced technology.

SECTION 6—NASA TECHNOLOGY

6.1 INTRODUCTION

The NHTSA/NASA memorandum of understanding stated that NASA would “identify key expertise and technology within the agency that can potentially contribute significantly to the improved effectiveness of the air bags.” To accomplish this, JPL contacted all of the NASA centers and provided them with information about the Advanced Air Bag Technology Assessment. These centers include:

- Ames Research Center (ARC)
- Goddard Space Flight Center (GSFC)
- Jet Propulsion Laboratory (JPL)
- Johnson Space Center (JSC)
- Langley Research Center (LaRC)
- Lewis Research Center (LeRC)
- Marshall Space Flight Center (MSFC) (which also represented Kennedy and Stennis Space Centers)

All NASA centers were contacted to identify applicable expertise and technology

Two methods were used to contact the centers.

JPL contacted the centers’ technology transfer offices, and the NASA Chief Engineer contacted the centers’ engineering, safety and mission assurance organizations. Each center conducted a search for technology relevant to the air bag problem. Both applicable expertise and technology were identified.

In addition, JPL searched two NASA technology databases for relevant capabilities and technologies. TechTracS.hq.nasa.gov provides information on completed NASA technology developments. A new technology database that is currently under development provides information on current technology developments.

Databases searched

Except for JPL, we were unable to visit other NASA centers and conduct seminars to solicit new ideas.

NASA has broad applicable capabilities

NASA has broad capabilities that can be applied to the development of improved air bags. At this time, two technologies are being transferred from NASA centers to suppliers where development is being undertaken. These are a capacitive proximity sensor developed at Goddard Research Center and a stereoscopic proximity and/or precrash sensor under development at JPL. Expertise and other technologies that have evolved from in-house NASA research and contracted efforts, including Small Business Innovative Research (SBIR), are described below.

6.2 EXPERTISE

NASA has relevant expertise in sensing, computing, control, neural networks, algorithm development, microelectronics, simulation, propellants, propulsion, inflatable systems, and systems analysis and engineering. Brief comments about these capabilities follow.

Significant applicable expertise exists within NASA, but it needs to be matched with industry requirements

Sensors. NASA has extensive expertise in a wide range of sensing and detection. The most relevant capabilities are those that have been or are being developed to support robotic operations. Obstacle avoidance sensors and algorithms are specifically applicable. The two sensors mentioned above are examples of these sensor types. Both GSFC and JPL have in-depth applicable capabilities.

Computing, Control, Neural Networks, Algorithm Development, Microelectronics. These capabilities apply to the control, diagnostics, and communication functions of the air bag system. Within the NASA community these capabilities are very broad and cover all related air bag functions. JPL has extensive applicable capabilities in all of the areas. At JPL neural networks have been applied to automobile engine control for a domestic OEM, and the Center for Space Microelectronics Technology (CSMT) at JPL develops solid-state components for space and other applications. ARC has been working with a contractor, IIS Corp., to develop mini-expert intelligent systems on a chip. The speed of the chips plus their low cost make them a candidate for application to air bag control logic systems.

Simulation. In its work NASA routinely performs a wide variety of simulations. Two commercial simulation codes that could have application to air bags were identified by LeRC. A finite-element structural code used at LeRC for bird-strike blade simulations may be applicable to the unfolding of the air bag. It could accommodate the large displacements that an air bag undergoes. A second possibility is a multiphysics code called Spectrum that is applicable to aeropropulsion problems. It may have application to the aero-

structural response of the inflator/air bag system. It might be able to simulate the entire transient event from initial air flow into the bag to full inflation. There is, of course, a very significant air bag simulation capability already in place, and it is constantly being improved. The above two codes have not been investigated in detail by JPL for their application to air bag simulation. Since the codes are commercially available, any air bag simulation developer could investigate their applicability.

Propellants, Propulsion. NASA and its predecessor organizations have been developing propulsion systems and propellants since before the space program started. The relevant capabilities include propellant formulation and forming, propulsion containment structural design, gas flow control and valve design, and filtering. This expertise includes all aspects of the air bag inflator design and development. Both MSFC and LeRC have broad propulsion and propellant capabilities. An initial search for cleaner and cooler-burning fuel by Marshall Space Flight Center (MSFC) did not produce any candidates. Researchers at LeRC have had discussions with one supplier regarding the use of gelled liquid propellants. The supplier's analysis implied that these propellants were too complex or expensive, but no details of the study were made available to LeRC. Further investigation of these propellants was not pursued.

Inflatable Systems. NASA has been developing and using inflatable systems for space operations. These systems have included air bags for Mars landing and an inflatable antenna (JPL). These NASA systems have requirements that are considerably different from those of automobile air bag systems. In particular, they do not need to be deployed rapidly as do automobile air bags. The deploying propellants also have different requirements. For example, toxicity may not be the problem in space systems that it is in automobile air bags. However, there are some common materials technologies that merit exchange of information. Also, MFSC has an experimental aerodynamics group with a good skill mix for analyzing chambered or other air bag designs.

Systems Analysis and Engineering. NASA has systems analysis and engineering capabilities in all centers. These capabilities are broad and could be applied to a wide range of problems both within industry and at NHTSA. Some specific examples of related capabilities are the following. JPL has been managing the development of a Variable Dynamics Testbed Vehicle for NHTSA. This project, together with the air bag assessment, has exposed JPL to crash avoidance sensing, which could be applicable to further

assessment of precrash sensors, as well as their integration with crash avoidance sensors. JPL's experience in the analysis of stochastic processes could be applied to further analyses of air bag systems, including development of a statistically based test program. Several centers, particularly those with requirements to deliver flight hardware, have experience in improving system reliability. An example is JPL's defect detection and prevention methodology, which could be used to determine the impact of test requirements on system protection.

Technology Transfer. Industry has access to NASA expertise and technology through the individual centers' technology transfer offices and publications, such as *NASA Tech Briefs*. Also, there are organizations within some centers, such as the JPL Technology Affiliates program, that provide mechanisms for companies to tap into NASA expertise to solve specific problems. The mechanisms are in place for identification and transfer of NASA technology to industry.

The need for NASA to work with OEMs and suppliers

The implementation of any new technology in vehicles requires that the technology be accepted by the suppliers and OEMs and developed into products by them. NASA technology and cost goals are quite different from those of automakers. These differences require identification of specific applicable NASA technology and significant dedication by developers to adapt the technology to automobile requirements.

Since the capabilities to develop automobile air bags reside in industry, any applicable NASA expertise would augment the industrial work. Also, since industry is the implementor of the technology, it must decide what NASA expertise or technology it can use. An exception to this would be that NHTSA could decide that some NASA capabilities could support their mission.

6.3 TECHNOLOGY

A capacitive detector

Two sensors initially developed by NASA are being further developed by suppliers for air bag applications. The "capaciflector," developed at Goddard Research Center, was licensed by Computer Application Systems, Inc. (CASI). CASI has contacted JPL and provided some information on their concept. They are working with a supplier who has worked with an OEM to install a capaciflector in a vehicle and test it. This system was considered in the technology characterization of Section 5 and its characteristics discussed in the Section 5.2.2.5 on capacitive sensors.

A stereoptic vision system

Stereoscopic vision systems have been under development at JPL for several years. The application for these systems is robotic obstacle avoidance for space systems. Development for application to military systems has also been conducted. This technology is currently being transferred to an air bag supplier who is evaluating its potential for proximity sensing and precrash sensing. This technology was also characterized in Section 5.2.2.5.

Improvements for air bag crash sensor

Canopus Systems Inc. (CSI), a LeRC accelerometry contractor, conducted work involving innovative technology improvements in air bag crash sensors. Canopus Systems, in conjunction with the University of Michigan Center for Integrated Sensors and Circuits (CISC), performed a Phase I SBIR study and developed several innovative designs, such as providing a digital output signal proportional to the crash force. These designs have application to automotive air bags. The Phase I study was completed, but Phase II was not funded. CSI has continued to work with CISC to develop innovative MEMS accelerometry systems.

Acoustic signature for crash sensing

Also, a JPL staff member suggested another approach for crash sensing. It uses the acoustic signature generated by the crushing of the vehicle during a crash to establish the crash severity.

Radar antenna

EMS Technologies, Inc. has had NASA funding to develop space communication systems—e.g., lightweight, multibeam antenna feed networks. A fabrication technique called unibody construction was used to integrate several beams into one, resulting in volume and weight savings. EMS has successfully demonstrated a radar antenna system that is low in cost, easy to produce, and has high RF performance capability for use in precrash sensing. The unibody construction method is the key to low-cost production.

At this time, JPL has found no technological breakthrough solution to the problem of air-bag-inflation-induced injuries from within NASA. It is hoped that this report will catalyze the identification of additional new concepts.

SECTION 7—INJURY RISK ASSESSMENT

7.1 METHODOLOGY

The injury risk assessment methodology for evaluating the effect of changes in critical parameters of the air bag system on the risk of occupant injury is illustrated in Figure 7-1. The critical parameters considered are: (1) whether the occupant is belted or unbelted, (2) the crash pulse shape, i.e., the deceleration-time profile, (3) proximity to the air bag module, (4) occupant category, (5) deployment time, i.e., the time at which inflation is initiated, as measured from the beginning of the crash pulse, (6) the inflator parameters, including mass flow-time profile and the temperature and molecular weight of output gas, and (7) air bag design.

Methodology determines effect of changes in critical parameters on air bag performance

The dummy response matrix shown in Figure 7-1 is derived from vehicle crash tests, sled tests to simulate vehicle crashes, static tests and computer simulations. The preferred source of dummy response data is vehicle crash tests; however, sled tests, static tests, and simulations can show dummy response to the critical parameters.

Dummy tests and simulations are the basis for the analysis

The dummy response matrix is transformed into an injury risk matrix by means of injury risk curves that are discussed in Appendix E. The injury risk matrix clearly presents the injury risk of different occupant

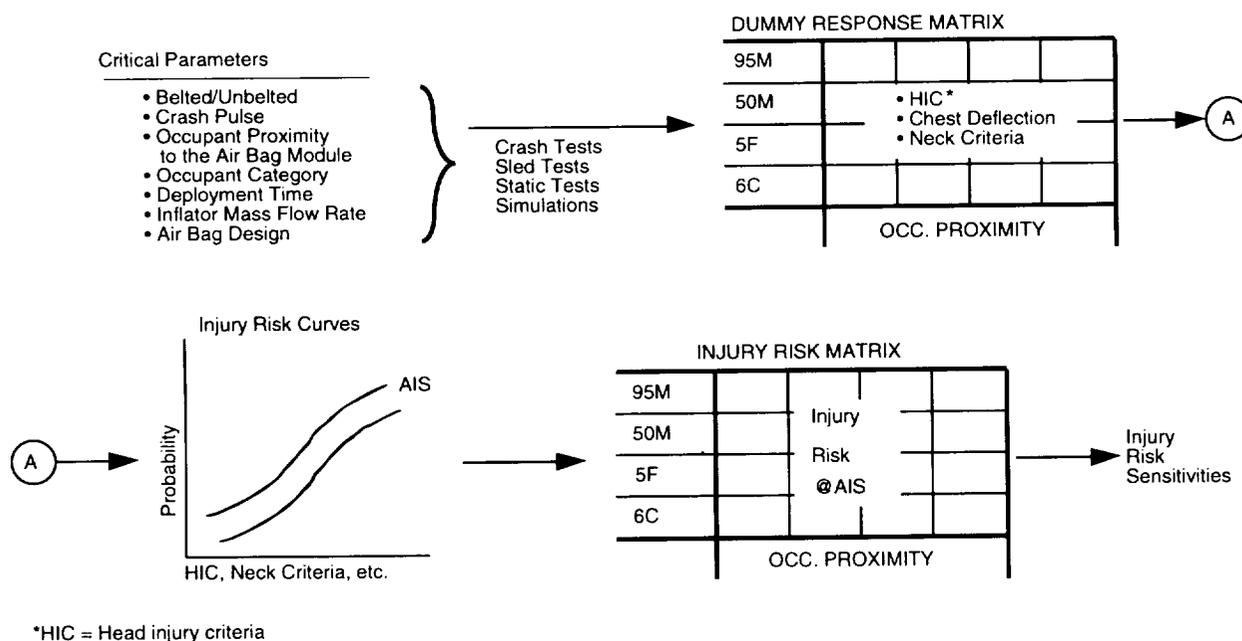


Figure 7-1. Injury Risk Assessment Methodology

Injury risk is determined

categories, i.e., 6-year-old child, 5th-percentile female, 50th-percentile male, and 95th-percentile male. Injury risk can be evaluated for selected sets of critical parameters so that sensitivities of injury risk to changes in critical parameters can be determined. These sensitivities will allow the impact of an advanced technology on injury risk across occupant categories to be assessed.

Requirements for advanced systems derive from injury risk sensitivities

Advanced air bag system technologies of interest include systems with the capability to: (1) determine occupant category and proximity, (2) modulate inflator output, and (3) optimize deployment time through real-time analysis of crash-pulse shape. The functional and performance requirements for systems to provide these advanced capabilities can be derived from the injury risk sensitivities. Conversely, injury risk sensitivities are necessary to assess capabilities of advanced technologies to mitigate injuries and enhance benefits.

Effects of alternative technologies assessed by changes in injury risk

Effects of alternative air bag system technologies on injury risk can be assessed by means of injury risk sensitivities. For example, consider a proximity sensing technology that could define occupant position with any needed accuracy and speed in conjunction with inflator technology that can modulate inflator output. Injury risk sensitivities for occupant categories with respect to inflator output and position can be used to assess injury risk implications for these technologies. Injury risk matrices for advanced technologies can be compared to those of present systems to highlight changes in injury risk that are attributable to each of an advanced technology across occupant categories.

Data sources

Data and information to support the generation of the dummy response sensitivities of Figure 7-1 were obtained from NHTSA publications, discussions and test results provided by Transport Canada, and discussions and information provided by the U. S. automobile manufacturers and air bag suppliers. In particular, data from car crash tests were provided by Transport Canada to characterize sensitivities of dummy response with respect to variation in crash pulse, inflator output, and proximity for the various occupants with three-point belts alone, and air bags plus three-point belts. In addition, results of computer simulations that were calibrated with crash or sled tests were provided by a U. S. automobile manufacturer. Additional car crash test results and sled test results were provided by U. S. automobile manufacturers and were also taken from various NHTSA publications and other references in the open literature. The results presented in Section 7.2 are based on car crash test results provided by Transport Canada [2], on results of various tests performed by NHTSA [22], and on the other information sources cited above.

7.2 OCCUPANT INJURY RISK

The results of vehicle crash tests performed by Transport Canada are shown in Tables F-1, F-2, and F-3, in Appendix F. The results of 48-km/h (30-mph) rigid frontal barrier (RFB) tests are shown in Tables F-1 and F-2 for belted 5% female and 50% male hybrid III dummies, respectively. Table F-3 shows responses of belted 5% female driver hybrid III dummies in deformable offset barrier (DOB) tests, with and without air bag deployment.

5% females are at high injury risk in 30-mph rigid barrier crashes, while 50% males are not at risk

The vehicle crash test results of Table F-1a show that head injury risk for the belted 5% female driver in 48-km/h (30-mph) rigid frontal barrier (RFB 30) crashes is comparatively small for both three-point belt (3PB) + air bag (AB) and 3PB cases. However, the vehicle crash test results of Table F-1a show that neck injury risk is typically high. Table F-1c shows that chest injury risk is high for vehicles A-96, G-96, I-96, K-97, and P-97.

The RFB 30 tests with the 50% male driver hybrid III dummy shown in Table F-2 show very low injury risk for the head, neck, and chest for all seven vehicles in the crash tests. This is in contrast to the results for 5% female drivers for the same vehicles. In particular, the neck injury risk of 5% female drivers for five of seven vehicles is higher than 10%, while the highest neck injury risk for the 50% male in the same seven vehicles is 0.3%.

Deformable offset barrier (DOB) crashes result in high injury risk for 5% females

The head, neck, and chest response of the 5% female driver in deformable offset barrier (DOB) tests are shown in Table F-3 for vehicle crashes with and without air bag deployment. The head injury risk of Table F-3a and the chest injury risk of Table F-3c are less than 6%. However, the neck injury risk shown in Table F-3b is extremely high in five of seven crashes with the air bag deployment. For each of the six vehicle types tested, the neck loads are significantly higher when the air bag deploys, even when neck injury risk is low.

Late deployments in DOB crashes cause the high injury risk

Table 7-1 shows 5% female driver injury risk for a deformable offset barrier test and a rigid frontal barrier test for six vehicle types with three-point belts and air bags. For four of the six vehicle types, neck injury risk is higher in the DOB crash test. In five of the six vehicle types tested, the neck injury risk is greater than 10% for either the DOB or RFB crash test. The injury risk for the 50% male in RFB 30 tests is shown in Table 7-2 for the same vehicle types as shown in Table 7-1. The 50% male driver injury risk is low in all cases. A paired comparison, with and without air bag deployment, of injury risk for the belted 5% female for five car models in DOB tests is shown in Table 7-3. Also shown is the time of deployment initiation

Table 7-1. Injury Risk for 5% Female Drivers in Rigid Frontal Barrier and Deformable Offset Barrier Vehicle Crash Tests Performed by Transport Canada

TC Test Number	Test Vehicle	Barrier Type (mph)	Restraint System	Head Injury Risk (%)	Neck Injury Risk (%)	Chest Injury Risk (%) AB ¹ /Belt ²
TC96-101	A-96	RFB(30)	3PB+AB	4.4	37.2	10.0/30.6
TC96-021	A-96	DOB(25)	3PB+AB	3.4	50.1	0.0/5.7
TC96-102	B-96	RFB(30)	3PB+AB	0.4	94.4	0.1/11.7
TC96-211	B-96	DOB(25)	3PB+AB	0.5	100	3.2/23.3
TC96-112	D-96	RFB(30)	3PB+AB	0.4	71.3	0.0/6.6
TC95-206	D-95	DOB(25)	3PB+AB	0.7	99.4	0.0/5.2
TC96-114	E-96	RFB(30)	3PB+AB	0.2	2.1	0.0/4.5
TC96-025	E-96	DOB(25)	3PB+AB	0.1	1.8	0.0/4.9
TC97-110	E-97	RFB(30)	3PB+AB	0.1	2.2	0.0/11.3
TC96-122	G-96	RFB(30)	3PB+AB	0.1	19.1	12.6/32.5
TC95-021	G-95	DOB(20)	3PB+AB	1.4	64.2	0.0/7.8
TC96-115	F-96	RFB(30)	3PB+AB	0.4	10.6	0.2/12.7
TC96-002	F-96	DOB(25)	3PB+AB	0.1	0.8	0.0/5.7
TC96-125	I-96	RFB(30)	3PB	4.3	11.6	27.0
TC97-108	P-97	RFB(30)	3PB	0.7	19.4	56.3

(1) Injury risk is calculated using AIS >3 rib fractures for distributed chest impacts in Figure E-4 in Appendix E.

(2) Injury risk is calculated using AIS >3 thoracic injury due to shoulder belt loading in Figure E-3 in Appendix E.

RFB: Rigid Frontal Barrier

DOB: Deformable Offset Barrier

3PB: Three-Point Belt

AB: Air Bag

Table 7-2. Injury Risk for 50% Male Drivers in 48-km/h (30-mph) [RFB(30)] Vehicle Crash Tests Performed By Transport Canada

TC Test Number	Test Vehicle	Barrier Type (mph)	Restraint System	Head Injury Risk (%)	Neck Injury Risk (%)	Chest Injury Risk (%) AB ¹ /Belt ²
TC96-102	B-96	RFB(30)	3PB+AB	0.2	0.0	0.0/2.1
TC96-112	D-96	RFB(30)	3PB+AB	0.1	0.2	0.0/6.9
TC96-114	E-96	RFB(30)	3PB+AB	0.3	0.1	0.0/4.6
TC96-115	F-96	RFB(30)	3PB+AB	0.2	0.2	0.0/8.6
TC96-125	G-96	RFB(30)	3PB+AB	0.2	0.3	0.0/5.5

(1) Injury risk is calculated using AIS >3 rib fractures for distributed chest impacts in Figure E-4 in Appendix E.

(2) Injury risk is calculated using AIS >3 thoracic injury due to shoulder belt loading in Figure E-3 in Appendix E.

RFB: Rigid Frontal Barrier

3PB: Three-Point Belt

AB: Air Bag

Table 7-3. Response of Belted 5% Female Hybrid III Dummy in Driver Seat (Near Position) in 40-km/h (25-mph) Deformable Offset Barrier (DOB25) and 32-km/h (20-mph) Deformable Offset Barrier (DOB20) Car Crash Tests Performed by Transport Canada

Dummy Response	Car Model											
	B-96		F-96		E-96		G-95	G-96	D-95	D-96		
	3PB + AB	3PB	3PB + AB	3PB	3PB + AB	3PB	3PB + AB	3PB	3 PB + AB	3PB	D-95	D-96
	DOB25	DOB25	DOB25	DOB25	DOB25	DOB25	DOB25	DOB25	DOB20	DOB25	DOB25	DOB25
	TC96-211	TC96-210	TC96-002	TC96-205	TC96-025	TC96-207	TC96-021	TC95-127	TC95-206	TC95-209		
Deployment initiation	100 ms*		30 ms*		40 ms*		91 ms*		56 ms*			
HIC 15	338	235	85	191	112	131	490	124	367	189		
Injury Risk, AIS 4+, %	0.5	0.3	0.1	0.2	0.1	0.1	1.4	0.1	0.7	0.2		
Neck Tension, N	4583	527	1225	892	1330	978	4170	809	2752	978		
Neck Ext. Moment, Nm	134	21	17	8	24	7	45	9	124	14		
Injury Risk, AIS 3+, %	>99.9	0.4	0.8	0.2	1.8	0.2	64.2	0.2	99.4	0.4		
Chest Deflection	37.6	13.1	23.1	22.9	21.9	20	25.9	12.2	22.4	20.6		
Injury Risk, AIS 3+, %			0		0		0.0/7.8		0.0/5.2			
AB ¹ /Belt ²	3.2/23.3	1.5	0.0/5.7	5.5	0.0/4.9	3.9	0.0/7.8	1.3	0.0/5.2	4.2		

(1) Injury risk is calculated using AIS ≥ 3 rib fractures for distributed chest impacts in Figure E-4.

(2) Injury risk is calculated using AIS ≥ 3 thoracic injury due to shoulder belt loading in Figure E-3.

*Air bag deployment time

3PB: Three-Point Belt

AB: Air Bag

of the air bag. In the three cases where time of deployment initiation exceeds 40 ms, the neck injury risk is very high. Late deployment allows the occupant to move closer to the air bag, thereby exacerbating the membrane effect with the attendant increase in neck loading.

A 5% female's close proximity to the air bag puts her at risk of injury

The injury risk of the belted 5% female drivers and the belted 50% male drivers for the same vehicle is shown in Table 7-4. The 50% male experiences small injury risk, while the 5% female has a very high neck injury risk. This difference may be due to the 5% female being closer to the air bag module due to seat position, coupled with the deployment time characteristics of this vehicle. A later deployment time that would not increase 50% male injury risk could substantially increase 5% female injury risk because the 5% female is closer to the air bag module when the crash begins. A similar injury risk comparison is shown in Table F-4 in Appendix F for a different vehicle. The vehicle of Table 7-5 shows low injury risk for both the 5% female driver and 50% male driver. This vehicle has an “early,” i.e., 40-ms, deployment initiation time in Table 7-3.

Depowered air bag significantly reduces injury risk for 5% female; belts alone are best

Table 7-6 shows 5% female driver injury risk for the same vehicle model for a baseline air bag with a three-point belt, a depowered air bag, and a three-point belt alone. Note that the lowest injury risk for the neck and the head is obtained with the three-point belt alone, and the lowest chest deflection is also with the three-point belt alone. Even though lowest chest deflection is obtained with the three-point

Table 7-4. Injury Risk Comparison for Fully Powered Air Bags of Vehicle B-96. Hybrid III 5% Female and 50% Male Drivers are Belted in 48-km/h (30-mph) Rigid Frontal Barrier Vehicle Crash Tests Performed by Transport Canada

	1*	2*	3*	4*
Hybrid III 95% Male				
Hybrid III 50% Male			Head: 0.2% Neck: 0.0% Chest: 0.0 ^A /2.1 ^B %	
Hybrid III 5% Female		Head: 0.4% Neck: 94.4% Chest: 0.1 ^A /11.7 ^B %		
Hybrid III 6-Year-Old				

*1 = Contact with module

*2 = Full forward (Typical position for Hybrid III 5% Female)

*3 = Midposition (Typical position for Hybrid III 50% Male)

*4 = Full rear (Typical position for Hybrid III 95% Male)

(A) Injury risk is calculated using AIS ≥ 3 rib fractures for distributed chest impacts in Figure E-4.

(B) Injury risk is calculated using AIS ≥ 3 thoracic injury due to shoulder belt loading in Figure E-3.

Table 7-5. Injury Risk Comparison for Fully Powered Air Bags of Vehicle E-96 with Early Deployment. Hybrid III 5% Female and 50% Male Drivers are Belted in 48-km/h (30-mph) Rigid Frontal Barrier Vehicle Crash Tests Performed by Transport Canada

	1*	2*	3*	4*
Hybrid III 95% Male				
Hybrid III 50% Male			Head: 0.3% Neck: 0.1% Chest: 0.0 ^A /4.6 ^B %	
Hybrid III 5% Female		Head: 0.2% Neck: 2.1% Chest: 0.0 ^A /4.5 ^B %		
Hybrid III 6-Year-Old				

*1 = Contact with module

*2 = Full forward (Typical position for Hybrid III 5% Female)

*3 = Midposition (Typical position for Hybrid III 50% Male)

*4 = Full rear (Typical position for Hybrid III 95% Male)

(A) Injury risk is calculated using AIS ≥ 3 rib fractures for distributed chest impacts in Figure E-4.

(B) Injury risk is calculated using AIS ≥ 3 thoracic injury due to shoulder belt loading in Figure E-3.

Table 7-6. Injury Risk Comparison for 5% Female Driver in 40 km/h (25-mph) Deformable Offset Barrier (DOB25) Vehicle Crash Tests with Fully Powered, Depowered (3PB + AB), and No Air Bag

Dummy Response	Car Model		
	D-95	D-97-D	D-96
	3PB + AB	3PB + AB	3PB
	TC96-206	TC97-200	TC96-209
HIC 15	367	N/A	189
Injury Risk, AIS 4+, %	0.7	N/A	0.2
Neck Tension, N	2752	902	978
Neck Ext. Moment, Nm	124	38.1	14
Injury Risk, AIS 3+, %	99.4	3.5	0.4
Chest Deflection	22.4	24.2	20.6
Injury Risk, AIS 3+, %			
AB ¹ /Belt ²	0.0/5.2	0.0/6.4	4.2

3PB = Three-point lap/shoulder belt

AB = Air bag

(1) Injury risk is calculated using AIS ≥ 3 rib fractures for distributed chest impacts in Figure E-3.

(2) Injury risk is calculated using AIS ≥ 3 thoracic injury due to shoulder belt loading in Figure E-3.

belt alone, the injury risk is higher because of the different injury risk curves used for air bag loading and shoulder belt loading. The depowered air bag does reduce the neck injury risk significantly relative to the baseline air bag, but the injury risk performance of the belt alone is superior to either the baseline or depowered air bag with belt for the 5% female in the DOB 25 test.

Neck injury risk for 5% female could be high in higher-severity crashes, i.e., RFB30

The results of three vehicle crash tests performed by Transport Canada with the 5% female driver dummy in vehicles with depowered air bag inflators are available to JPL. Two of these three depowered tests were DOB 25 crashes, and one was an RFB 30 crash. One of the DOB 25 tests is shown in Table 7-6 for vehicle D (test TC97-200). The other DOB 25 depowered crash test was of vehicle E, and is not shown in any table. The DOB 25 test of vehicle D with a 25% depowered inflator produced a substantial reduction in neck injury risk—down to 3.5% from the 99.4% for a fully powered inflator shown in Table 7-6 (test TC95-206). The RFB 30 depowered inflator crash test of vehicle D produced an unacceptably high neck injury risk at 51%. The higher-severity RFB 30 crash produces more rapid movement of the occupant toward the air bag module. If deployment time is late, the occupant will be closer to the module in the more severe RFB 30 crash. This could be a factor in the high injury risk with the depowered inflator in the RFB 30 crash of vehicle D. The other DOB 25 test with a depowered inflator of vehicle E produced essentially the same injury risk as the fully powered inflator of vehicle E shown in Table 7-1 (test TC96-025).

Unrestrained passengers at greater risk than drivers

Table 7-7 shows injury risk for the unbelted 50% male driver and passenger for baseline, depowered, and no air bag cases in RFB 30 vehicle crash tests. The 50% male driver has a low risk of injury for head and neck, even without any restraint at all. However, the 50%

Table 7-7. Responses of Unbelted 50% Male Driver and Passenger and Injury Risk For 48-km/h (30-mph) Rigid Frontal Barrier Crash Tests*

Dummy Response	50% Male Driver			50% Male Passenger		
	Baseline	Depowered	No Air Bag	Baseline	Depowered	No Air Bag
HIC 15	280	560	850	150	480	850
Injury Risk, AIS 4+, %	0.4	2.1	8.7	0.1	1.3	8.7
Neck Tension, N	1518	1386	1122	297	3696	5412
Neck Ext. Moment, Nm	34	45	35	18	49	185
Injury Risk, AIS 3+, %	0.5	0.8	0.3	0.0	6.9	95.5
Chest Deflection	32	24	45	17	10	18.2
Injury Risk, AIS 3+, %	0.0	0.0	38.4	0.0	0.0	3.1

* Vehicle crash test performed by a U. S. automobile manufacturer.

male passenger has high injury risk for the head and neck with no belt and no bag.

Early deployment required for low injury risk

Tables 7-8 and 7-9 show injury risk for the 50% male and the 5% female drivers in 17G sled tests with preset deployment timing. These results indicate that an airbag reduces injury risk for unbelted drivers and passengers, providing that deployment initiation is sufficiently early in the crash.

Depowered air bag can increase chest injury risk for the unbelted 5% female

Tables 7-10 and 7-11 show injury risk from computer simulations for the 50% male and the 5% female drivers for baseline and depowered inflators for different crash pulses. Injury risk of the 50% male for the head, neck, and chest does not change significantly with respect to inflator output, crash pulse, or whether the occupant is belted or unbelted. However, the chest injury risk for the unbelted 5% female does show an increase with the depowered inflator. Injury

Table 7-8. Responses of 50% Male and 5% Female Unbelted Drivers and Injury Risk For 17G Sled Tests with 125-ms Pulse (from Reference [22])

Dummy Response	50% Male Driver			5% Female Driver		
	Inflator Output			Inflator Output		
	350 x 22	300 x 13	No Air Bag	350 x 22	300 x 13	No Air Bag
HIC 15	134	231	553	93	122	269
Injury Risk, AIS 4+, %	0.1	0.3	2.0	0.1	0.1	0.3
Neck Tension, N	750	761	1821	924	808	707
Neck Ext. Moment, Nm	14	13	72	39	11	16
Injury Risk, AIS 3+, %	0.1	0.1	4.0	3.9	0.2	0.3
Chest Deflection	29	24	40	27	31	47
Injury Risk, AIS 3+, %	0.0	0.0	27.8	0.0	0.2	43.0

Table 7-9. Responses of 50% Male and 5% Female Unbelted Hybrid Dummy Passenger For 17G Sled Tests with 125-ms Pulse (from Reference [22])

Dummy Response	50% Male Passenger			5% Female Passenger		
	Inflator Output			Inflator Output		
	340 x 8.2	285 x 5.2	No Air Bag	340 x 8.2	285 x 5.2	No Air Bag
HIC 15	80	98	462	50	54	627
Injury Risk, AIS 4+, %	0.1	0.1	1.2	0.1	0.1	3.0
Neck Tension, N	924	528	1504	778	381	1177
Neck Ext. Moment, Nm	39	35	221	14	10	100
Injury Risk, AIS 3+, %	0.4	0.2	82	0.3	0.1	75
Chest Deflection	12	6	22	14	6	44
Injury Risk, AIS 3+, %	0.0	0.0	5.0	0.0	0.0	36.2

Table 7-10. Response of Unbelted 5% Female Hybrid III Dummy in Driver Seat for Two Different Air Bag Inflators for 48-km/h (30-mph) Rigid Barrier and 40-km/h (25-mph) Generic Collisions. Dummy Response from Simulations of Reference [8]

Dummy Response	Inflator Output											
	350 x 22						300 x 13					
	Bag Only			3PB + Bag			Bag Only			3PB + Bag		
	G25	R30	R35	G25	R30	R35	G25	R30	R35	G25	R30	R35
HIC 15	90	130	174	97	132	202	76	228	236	77	321	333
Injury Risk, AIS 4+, %	0.1	0.1	0.2	0.1	0.1	0.2	0.1	0.3	0.3	0.1	0.5	0.5
Neck Tension, N	903	1029	1560	976	1130	1663	567	881	895	784	1104	1127
Neck Ext. Moment, Nm	14	35.6	44.7	13.5	34.5	50.8	2.9	9	9.8	1	4.4	8.5
Injury Risk, AIS 3+, %	0.3	3.4	11.9	0.4	3.5	18.7	0.0	0.3	0.2	0.1	0.2	0.3
Chest Deflection	15.8	36	34.4	21.8	26.8	27.6	30.1	44.9	44.4	22.3	35.6	36.1
Injury Risk ¹ , AIS 3+, %	0.0	1.8	1.0	0.0	0.0	0.0	0.1	22.7	20.4	0.0	1.5	1.9
Injury Risk ² , AIS 3+, %				4.9	8.6	9.4				5.2	19.8	20.7

(1) Injury risk is calculated using AIS ≥ 3 rib fractures for distributed chest impacts in Figure E-4.

(2) Injury risk is calculated using AIS ≥ 3 thoracic injury due to shoulder belt loading in Figure E-3.

3PB: Three-Point Belt

Table 7-11. Response of Unbelted 50% Male Hybrid III Dummy in Driver Seat for Two Different Air Bag Inflators for 48-km/h (30-mph) Rigid Barrier and 40-km/h (25-mph) Generic Collision. Dummy Response from Simulations of Reference [8]

Dummy Response	Inflator Output											
	350 x 22						300 x 13					
	Bag Only			3PB + Bag			Bag Only			3PB + Bag		
	G25	R30	R35	G25	R30	R35	G25	R30	R35	G25	R30	R35
HIC 15	129	298	368	139	544	554	133	389	428	178	573	577
Injury Risk, AIS 4+, %	1.1	0.4	0.7	0.1	1.9	2.0	0.1	0.8	1.0	0.2	2.3	2.3
Neck Tension, N	1044	1829	1828	1075	1528	1568	1226	1622	2041	1220	1748	2060
Neck Ext. Moment, Nm	18.3	30.0	35.3	7.4	17.8	16.5	16.3	24.8	24.2	5.0	9.9	13.4
Injury Risk, AIS 3+, %	0.1	0.6	0.8	0.1	0.2	0.2	0.1	0.3	0.5	0.1	0.2	0.3
Chest Deflection	24.7	26.4	26.7	26.2	33.1	34	23.8	23.9	24.9	29.4	36.5	37.5
Injury Risk ¹ , AIS 3+, %	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2
Injury Risk ² , AIS 3+, %					16.0	17.3				11.3	21.4	23.1

(1) Injury risk is calculated using AIS ≥ 3 rib fractures for distributed chest impacts in Figure E-4.

(2) Injury risk is calculated using AIS ≥ 3 thoracic injury due to shoulder belt loading in Figure E-3.

3PB: Three-Point Belt

risk for the belted 5% female is essentially invariant with respect to inflator output and crash pulse type.

Depowering does not reduce injury risk for 6-year-old child

Table 7-12 shows the results of static air bag deployment tests for the 6-year-old child dummy. Dummy positions are shown in Appendix E. In positions 1 and 2, depowering by 30% does not reduce neck injury risk to acceptable levels. The normal power and 30% depowered test results show high levels of neck injury risk, which is consistent with the evidence from incidents in which children have experienced fatal neck injuries from being in close proximity to deploying air bags.

Comparison of NHTSA and Mertz curves

Tables 7-13 and 7-14 compare the injury risks as calculated by the NHTSA curves and the Mertz curves from the dummy response data given in [26]. There is no significant difference in the risk of AIS 4+ head injury between the NHTSA curves and Mertz curves. However, the risk of chest injury using chest acceleration and the NHTSA curves greatly exceeds the risk of chest injury using chest deflection and the Mertz curves. As discussed in Appendix E, chest deflection using the Mertz curves gives a more realistic indicator of thoracic injury.

Summary of depowering results

Table 7-15 shows the injury risk for different occupant categories for fully powered air bags, and Table 7-16 shows the corresponding injury risk for depowered air bags. The 30% depowered air bag results in a significant decrease in injury risk for 5th-percentile female dummies while very slightly increasing injury risk for 50th-percentile male dummies. Child injury risk is not significantly affected by this level of depowering.

7.3 SENSITIVITY OF OCCUPANT INJURY RISK TO CHANGES IN CRITICAL PARAMETERS

No characterization of critical parameters was identified

7.3.1 Critical Parameters. The more important parameters that affect air bag system performance as measured by occupant injury risk include deployment time, inflator output, occupant proximity to the air bag module during inflation, occupant belt status (belted or unbelted), crash pulse shape, vehicle velocity change during the crash, occupant category, and air bag design. No comprehensive, systematic characterization of the effects of these parameters, considering interactions, on occupant injury risk was found during the course of this study. Such a characterization of the sensitivity of occupant injury risk to a variation of these critical parameters is not available in the open literature or from NHTSA. If any of the air bag suppliers or automobile manufacturers have developed such a systematic characterization, it was not made available of the JPL team when requested.

Table 7-12. Static Air Bag Deployment Tests by NHTSA for Configuration B-94 with 6-Year-Old Hybrid III Dummy in Three Positions Adjacent to the Air Bag Module. Dummy Positions are Shown in Figure E-11. (From Reference [22])

Dummy Response	Position 1			Position 2			Position 3		
	B-94	B-94 30% Depowered	B-94 60% Depowered	B-94 Normal	B-94 30% Depowered	B-94 60% Depowered	B-94 Normal	B-94 30% Depowered	B-94 60% Depowered
	*HIC 15 Injury Risk, AIS 4+, %	720 4.8	129 0.1	16 0.0	1225 31.3	238 0.3	53 0.1	683 4.0	27 0.1
Neck Tension, N Neck Ext. Moment, Nm Injury Risk, AIS 3+, %	6184 175 >99.9	2383 83 99.8	1279 31 16.0	6661 68 >99.9	2069 51 77.8	836 20 2.4	2152 40 57.9	1257 39 29.0	146 5 0.0

*HIC 15 is estimated from HIC 36 using 0.8 as a scaling factor.

Table 7-13. Responses of 5% Female, 50% Male, and 95% Male Dummy Driver and Passenger in Rigid Barrier 48-km/h (30-mph) and 56-km/h (35-mph) Rigid Barrier Tests Performed by NHTSA. Injury Risk Values are Based on NHTSA Developed Injury Risk Curves

Car Model	Impact Speed, mph	Seating	Belt Status	Dummy Type	HIC 36	HIC 15	Head Injury Risk (%)	Chest G's	Chest Injury Risk (%) AIS ≥ 3	Femur, N	Chest Deflection, mm
Taurus	30	Driver	Unbelted	5th Female	156	124.8	0.0	43.5	5	4483	24
Taurus	30	Passenger	Unbelted	95th Male	1009	807.2	11.2	44.6	6	9372	18
Taurus	30	Driver	Unbelted	95th Male	462	369.6	0.6	43.4	5	9730	3
Taurus	30	Passenger	Unbelted	5th Female	319	255.2	0.1	49.9	8	4811	17
Taurus	30	Driver	Unbelted	50th Male	427	341.6	0.4	48	8	7638	N/A
Taurus	30	Passenger	Unbelted	50th Male	485	388	0.8	32	3	5547	N/A
Taurus	35	Driver	Belted	5th Female	234	187.2	0.0	53.6	65	3367	34
Taurus	35	Passenger	Belted	95th Male	261	208.8	0.0	43.1	51	5093	43
Taurus	35	Driver	Belted	95th Male	584	467.2	1.7	48	57	7780	48
Taurus	35	Passenger	Belted	5th Female	637	509.6	2.4	47.2	56	3212	4

Dummy responses from Reference [26].

Injury risk calculated from the NHTSA developed curves in Figure E-16 for head and Figures E-14 and E-15 for chest.

Table 7-14. Responses of 5% Female, 50% Male, and 95% Male Dummy Driver and Passenger in Rigid Barrier 48-km/h (30-mph) and 56-km/h (35-mph) Rigid Barrier Tests Performed by NHTSA. Injury Risk Values are Based on Injury Curves Developed by Mertz

Car Model	Impact Speed, mph	Seating	Belt Status	Dummy Type	HIC 36	HIC 15	Head Injury Risk (%)	Chest G's	Femur, N	Chest Deflection, mm	Chest Injury Risk (%) AB/Belt ²
Taurus	30	Driver	Unbelted	5th Female	156	124.8	0.1	43.5	4483	24	0.0
Taurus	30	Passenger	Unbelted	95th Male	1009	807.2	7.2	44.6	9372	18	0.0
Taurus	30	Driver	Unbelted	95th Male	462	369.6	0.7	43.4	9730	3	0.0
Taurus	30	Passenger	Unbelted	5th Female	319	255.2	0.3	49.9	4811	17	0.0
Taurus	30	Driver	Unbelted	50th Male	427	341.6	0.6	48	7638	N/A	N/A
Taurus	30	Passenger	Unbelted	50th Male	485	388	0.7	32	5547	N/A	N/A
Taurus	35	Driver	Belted	5th Female	234	187.2	0.2	53.6	3367	34	0.8/17.3
Taurus	35	Passenger	Belted	95th Male	261	208.8	0.2	43.1	5093	43	0.3/34.0
Taurus	35	Driver	Belted	95th Male	584	467.2	1.2	48	7780	48	1.4/5.3
Taurus	35	Passenger	Belted	5th Female	637	509.6	1.6	47.2	3212	4	0.0/0.3

Dummy responses from Reference [26].

Injury risk calculated from the Mertz curves in Figure E-1 for head.

- (1) Injury risk is calculated using AIS \geq 3 rib features for distributed chest impacts in Figure E-4.
- (2) Injury risk is calculated using AIS \geq 3 thoracic injury due to shoulder belt loading in Figure E-3.

Table 7-15. Injury Risk Comparison for Fully Powered Air Bags. Belted Hybrid III 5% Female^A and Unbelted Hybrid III 50% Male Drivers^B are in 32-km/h (20-mph) Deformable Offset Barrier and 48-km/h (30-mph) Rigid Frontal Barrier Vehicle Crash Tests, Respectively. Hybrid III 6-Year-Old Responses Are From Static Test in Reference [22]

	1*	2*	3*	4*
Hybrid III 95% Male				
Hybrid III 50% Male			Head: 0.4% Neck: 0.5% Chest: 0.0%	
Hybrid III 5% Female		Head: 0.7% Neck: 94.4% Chest: 0.0 ^C /5.2 ^D %		
Hybrid III 6-Year-Old	Head: 4.8% Neck: >99.9%			

*1 = Contact with module

*2 = Full forward (Typical position for Hybrid III 5% Female)

*3 = Midposition (Typical position for Hybrid III 50% Male)

*4 = Full rear (Typical position for Hybrid III 95% Male)

(A) Vehicle crash tests from Reference [2].

(B) Vehicle crash tests performed by U. S. automobile manufacturer.

(C) Injury risk is calculated using AIS ≥ 3 rib fractures for distributed chest impacts in Figure E-4.

(D) Injury risk is calculated using AIS ≥ 3 thoracic injury due to shoulder belt loading in Figure E-3.

Table 7-16. Injury Risk Comparison for About 25% Depowered Air Bags. Belted Hybrid III 5% Female^A and Unbelted Hybrid III 50% Male Drivers^B are in 32-km/h (20-mph) Deformable Offset Barrier and 48-km/h (30-mph) Rigid Frontal Barrier Vehicle Crash Tests, Respectively. Hybrid III 6-Year-Old Responses Are From Static Test in Reference [22]

	1*	2*	3*	4*
Hybrid III 95% Male				
Hybrid III 50% Male			Head: 2.1% Neck: 0.8% Chest: 0.0%	
Hybrid III 5% Female		Neck: 3.5% Chest: 0.0 ^C /6.4 ^D %		
Hybrid III 6-Year-Old	Head: 0.1% Neck: >99.8%			

*1 = Contact with module

*2 = Full forward (Typical position for Hybrid III 5% Female)

*3 = Midposition (Typical position for Hybrid III 50% Male)

*4 = Full rear (Typical position for Hybrid III 95% Male)

(A) Vehicle crash tests from Reference [2].

(B) Vehicle crash tests performed by U. S. automobile manufacturer.

(C) Injury risk is calculated using AIS ≥ 3 rib fractures for distributed chest impacts in Figure E-4.

(D) Injury risk is calculated using AIS ≥ 3 thoracic injury due to shoulder belt loading in Figure E-3.

To meet a goal of protecting the public from injury during vehicle crashes, air bag performance must be characterized and understood (1) for occupants of different sizes who sit at different distances from the air bag module, (2) for vehicle crashes of differing severity ranging from low-speed vehicle-to-vehicle crashes to high-speed, rigid-barrier crashes, (3) for different ambient temperatures because temperature has a large effect on inflator gas output characteristics, and (4) for belted and unbelted occupants. The air bag systems currently in the American vehicle fleet have been optimized for the 50th-percentile male without a seat belt in a 48-km/h (30-mph) rigid frontal barrier crash at ambient temperature.

Need to increase air bag system robustness

The performance of present air bag systems can be severely degraded by variation of any of the parameters mentioned above. The introduction of advanced technology must dramatically increase the robustness of air bag system performance with respect to variation of critical parameters encountered during public usage of automobiles.

7.3.2 Deployment Time. The performance of an air bag system expressed in terms of occupant injury risk is strongly affected by the time at which inflation is initiated, i.e., the deployment time. At the beginning of a crash, an occupant begins to move forward relative to the vehicle. The distance between the occupant and the air bag module decreases as the occupant moves forward. If the deployment time is late in the crash, the occupant can be close enough to the air bag module to interact with the inflating air bag and can experience inflation-induced injuries.

Deployment times exceeding 40 ms can cause severe injury

Deployment times are shown in Table 7-17 for six vehicles with conventional air bags tested in deformable offset barrier crashes with 5% female dummies by Transport Canada. The deformable offset barrier crash tests are representative of the “softer” vehicle-to-vehicle crashes that commonly occur. In four of the tests the deployment time exceeded 40 ms. In those tests, neck injury risk is extremely high, while in the tests with early deployment time the injury risk is low. Late deployment results in the occupant moving into the path of the deploying air bag, increasing injury risk potential.

Results of reference [23] show that deployment time variability increases inversely with crash severity. That is, as the crash severity is reduced, variability in deployment time increases. Well over 90% of automobile crashes occur with vehicle ΔV less than 48 km/h (30 mph), and about 70% of automobile crashes occur with vehicle ΔV between 14.5 km/h (9 mph) and 35.4 km/h (22 mph). If late deployment is as prevalent as the Transport Canada tests and the

Table 7-17. Injury Risk of Belted 5% Female Driver (Near Positions) vs. Air Bag Deployment Time in 40-km/h (25-mph) Deformable Offset Barrier (DOB25) and 32-km/h (20-mph) Deformable Offset Barrier (DOB20) Car Crash Tests Performed by Transport Canada

Dummy Response	Car Model					
	B-96	F-96	E-96	G-95	D-95	Q-96
	3PB + AB	3PB + AB	3PB + AB	3PB + AB	3PB + AB	3PB + AB
	DOB25	DOB25	DOB25	DOB20	DOB25	DOB25
	TC96-211 100 ms*	TC96-002 30 ms*	TC96-025 40 ms*	TC96-021 91 ms*	TC95-206 56 ms*	TC96-024 100 ms*
HIC 15	338	85	112	490	367	240
Injury Risk, AIS 4+, %	0.5	0.1	0.1	1.4	0.7	0.3
Neck Tension, N	4583	1225	1330	4170	2752	2676
Neck Ext. Moment, Nm	134	17	24	45	124	67
Injury Risk, AIS 3+, %	>99.9	0.8	1.8	64.2	99.4	62.2
Chest Deflection	37.6	23.1	21.9	25.9	22.4	33.9
Injury Risk ¹ , AIS 3+, %	3.2	0.0	0.0	0.0	0.0	0.8
Injury Risk ² , AIS 3+, %	23.3	5.7	4.9	7.8	5.2	17.2

*Air Bag Deployment Time

(1) Injury risk is calculated using AIS ≥ 3 rib fractures for distributed chest impacts in Figure E-4.

(2) Injury risk is calculated using AIS ≥ 3 thoracic injury due to shoulder belt loading in Figure E-3.

3PB: Three-Point Belt

AB: Air Bag

reference [23] would indicate, a substantial number of occupants are being exposed to a significant risk of inflation-induced injury in crashes that commonly occur.

Advanced technology may reduce deployment time variability

Advanced technology may reduce deployment time variability and reduce the adverse effects of variability. Improved crash sensor algorithms are intended to provide more accurate and timely detection of crash severity, which should reduce the deployment time variability. However, there is no data available to evaluate the extent to which these intentions are achievable. The development of new compartmentalized bags may reduce the keep-out zone and thus permit later deployments without serious injury risk.

7.3.3 Inflator Parameters. The inflator output gas mass flow versus time profile, the gas molecular weight, and gas temperature all affect the forces exerted on an occupant during an occupant/air bag interaction. Gas is exhausted from the air bag through the bag vent holes, so the rate of pressure rise inside the bag is determined by inflator gas output and vent area.

A deploying air bag can cause inflation-induced injury during the inflation process when the “membrane effect” occurs. The “membrane

Forces on an occupant are strongly affected by inflator gas mass flow versus time

effect” results from the occupant being close enough to the air bag module to interact with the air bag before it can reach the size and shape that it would have when fully inflated. If an occupant is close enough to the module for a deploying air bag to become fully extended while enveloping an occupant’s head and neck, the increasing gas pressure in the bag will act to forcibly expel the occupant. The forces exerted on the occupant are strongly affected by inflator gas output characteristics, in particular the output gas mass flow versus time profile.

Reduced injury risk from depowered air bags

By reducing inflator rise rate and peak pressure, a reduction of neck injury risk can be achieved for 5% female drivers. Available evidence indicates a reduction of injury risk with depowered air bags in DOB 25 tests and static tests. However, the single RFB 30 vehicle crash test with a depowered air bag that is available to JPL indicates high 5% female neck injury risk at 51%, although it is reduced from 99.4% with a fully powered inflator. Tables 7-16 and 7-17 illustrate a reduction in injury risk with depowering. Both 5% females and 50% male drivers show acceptable injury risk, but child passengers remain at considerable risk.

Depowering typically means that the inflator output has been reduced from that of, say, 400 x 21 or 350 x 22 to that of 300 x 12 or 285 x 5*. With lower bag pressure and smaller pressure rise rates, a concern arises that larger occupants such as the 50% and 95% males could “bottom out” the air bag and experience high loads during more severe crashes.

The information from a 48-km/h (30-mph) rigid frontal barrier crash test, a 17G sled test, and calibrated simulations that is presented in Tables 7-7, 7-8, and 7-11, respectively, indicates that injury risk does not increase in any significant way for the 50% male in crashes up to the severity of the RFB 30 crash test. The HIC for the 50% male does increase slightly for the depowered cases shown in Tables 7-7, 7-8, and 7-11, while chest deflection decreases somewhat. These changes in HIC and chest deflection do not cause any significant changes in injury risk.

For the larger 95% male occupant, no information is available to make an assessment. However, the rigid frontal barrier car crash tests shown in Table 7-14 indicate that the unbelted 95% male passenger has a comparatively high HIC measurement, which may increase with depowered air bags. Table 7-14 also shows a significant risk of

* Peak pressure (kPa) x pressure rise rate (kPa/ms) in a standard tank test

chest injury for belted 5% female and 95% male occupants in 56-km/h (35-mph) rigid frontal barrier crash tests.

The effect of depowering inflators by about 25% is summarized in Table 7-16. With depowered inflators, the injury risk for the 50% male driver is essentially unchanged, while that for the 5% female driver is substantially reduced, and injury risk for the 6-year-old child passenger in close proximity to the module remains extremely high. Reducing inflator power by about 25% from pre-1997 levels increases robustness of airbag system performance for the 50% male drivers with respect to departures of critical parameters from their design point values established for the 50% male in the RFB 30 crash. Robustness may be decreased for other crash situations, i.e., for higher-speed crashes and larger occupants. JPL had no data to evaluate this effect.

Inflator unit-to-unit variability is high; with this variability, benefits of depowering are problematic

Inflator-to-inflator output variability of inflators with the same specifications appears to be a significant problem. Data made available to JPL from testing of about 50 inflators of the same specifications and from the same manufacturing lot (Figure 5-3) shows that total gas output and pressure rise rate vary significantly. The “three-sigma” variability of this data is $\pm 13\%$. Larger variabilities occur during pressure rise and with variation in temperatures. This level of variability would make the benefits of depowering problematic. Inflator output variability of this magnitude would also interfere with the effectiveness of dual-stage inflators as a means of extending air bag protection to higher-severity crashes.

Variability in inflator output will result in variability of measured dummy response. Dummy response measurements from a series of six static tests with an out-of-position 50% male dummy were provided to JPL by an OEM. The tests were performed with six inflators of the same type and from the same lot and with the dummy in the same position for each test. The variability of dummy response was significant from test to test. The coefficient of variation (the ratio of the standard deviation to the mean) for the six tests was 39% for neck extension moment, 21% for neck tension, 36% for viscous coefficient (V^*C), and 32% for HIC 36. Due to the nature of dummy response, some variation of response measures would be expected even if inflator output did not change from test to test. However, in these six tests inflator output variability is the likely source of the high variability of dummy response.

If inflator output variability is as large as these data suggest, high priority should be given to resolving this problem. The inflator

variability increases at lower temperature and also increases at higher temperature. The effects of temperature on inflator output should be understood and incorporated into the deployment strategy for advanced air bag systems. Through continuing development and implementation of alternative inflator concepts, inflator output variability should be effectively resolved.

Close proximity to a deploying air bag module can cause extremely high injury risk

7.3.4 Proximity. Occupants that are close enough to interact with the deploying air bag as it is being inflated can experience inflation-induced injuries due to the “punch-out” phase of deployment and due to the membrane effect. The membrane effect is discussed in section 7.3.3 above. The punch-out phase occurs as the folded air bag initially emerges from the module. During the punch-out phase, pressure in the air bag module builds up until sufficient force is generated to tear the module cover or open the air bag door. The air bag can emerge from the module with force sufficient to cause the air bag module door to shatter a car’s windshield if the door hits it. The force imparted to a 6-year-old child dummy by even a depowered inflator is high enough to cause extremely high injury risk.

The force exerted on an occupant by a deploying air bag increases when an occupant is closer to the module at the beginning of deployment. Static tests with 5% female dummies were performed by Transport Canada to measure dummy response as a function of distance from the air bag module. Figures F-1 through F-5 in Appendix F show dummy response as a function of upper sternum-to-module distance. The dummy response measurements include neck tension, neck extension moment, sternal deflection, and peak head acceleration. The neck injury risk and chest injury risk calculated using Mertz’ injury risk curves are shown in Figures 7-2 and 7-3 for fully powered and depowered air bag modules, respectively, for two vehicles.

Air bag system design can reduce injury risk

The neck injury risk in Figure 7-2 for the fully powered module increases abruptly as sternum-to-module distance decreases below about 130 mm. There is a significant difference between vehicles D and E, with vehicle E showing much lower injury risk. Chest injury risk, shown in Figure 7-2, also begins to increase at 130 mm for vehicle D but does not increase significantly for vehicle E. For both vehicles, neck and chest injury risks are much lower with depowered modules. The neck and chest injury risks for vehicle E with the depowered module are not significant for a sternum-to-module distance of 70 mm. There is no data for distances less than 70 mm. The superior performance of vehicle E in these static tests is attributable to the air bag module design. The module is recessed in

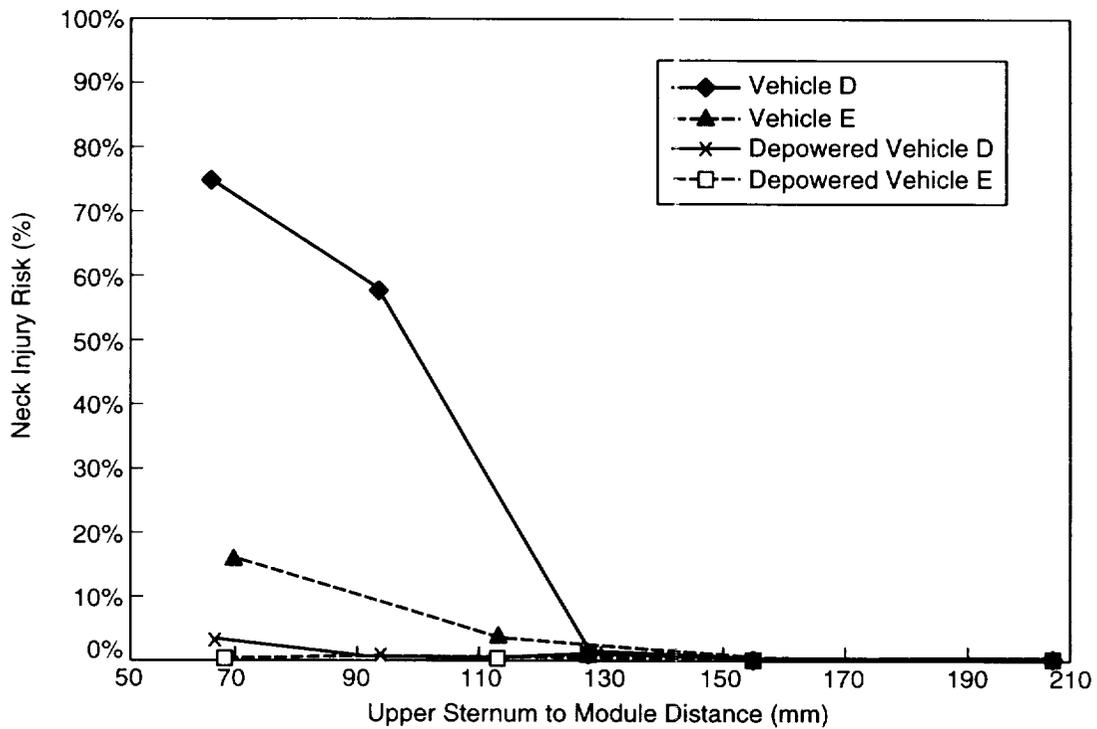


Figure 7-2. Neck Injury Risk of 5% Female in Static Out-of-Position Air Bag Deployment Tests as a Function of Sternum-to-Module Distance. Tests performed by Transport Canada

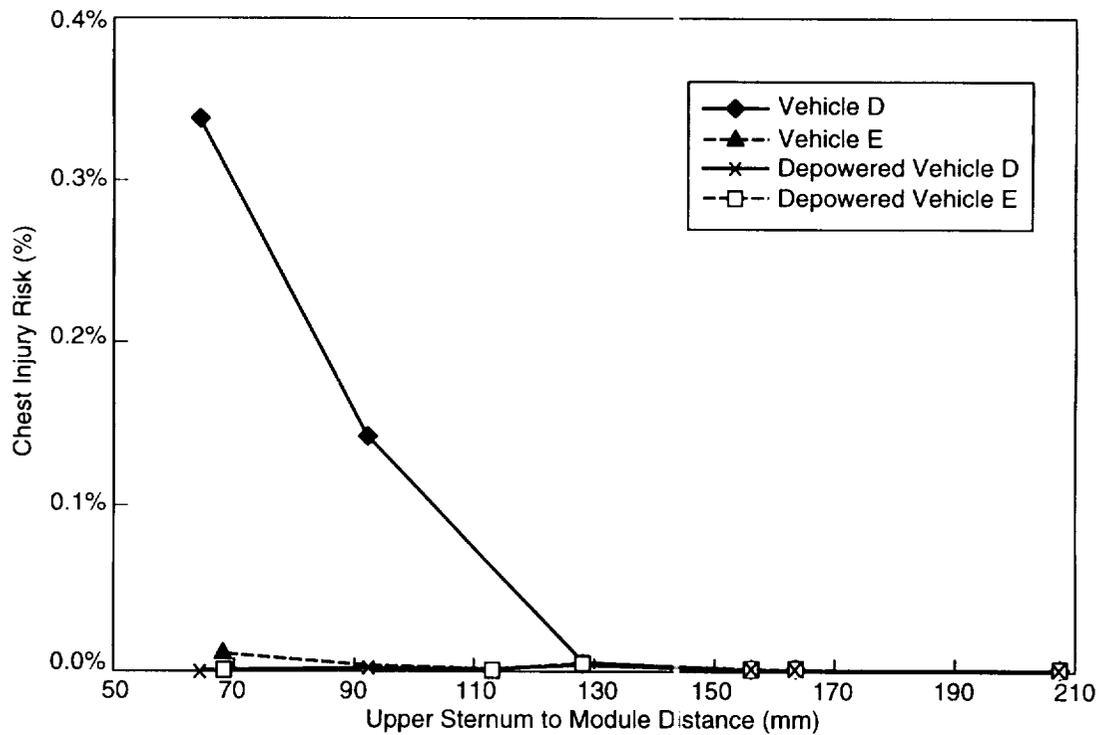


Figure 7-3. Chest Injury Risk of 5% Female in Static Out-of-Position Air Bag Deployment Tests as a Function of Sternum-to-Module Distance. Tests performed by Transport Canada

the steering wheel hub, and the air bag initially deploys radially when the occupant is near the module.

7.3.5 Belt Status. Belts limit the extent to which occupants can move closer to the air bag during a crash. Since inflation-induced injuries are the result of close proximity to the air bag module during air bag inflation, limiting occupant movement toward the module during a crash can greatly reduce occupant interaction with the inflating air bag.

If the initial position of the occupant is sufficiently close to the module, occupant interaction with the inflating air bag is difficult, if not impossible, to avoid. In this situation, the inflating air bag must not exert excessively high forces on the occupant if inflation-induced injuries are to be avoided. In most cases 50% male occupants are at a very small risk of inflation-induced injuries with or without belts unless they are out of position and very near the deploying air bag.

The 5% female driver normally sits so close to the air bag module that inflation-induced injury with a fully powered module of conventional design is likely to occur even when she is belted. With depowering, 5% female drivers will have low probability of injury risk unless they are out of position and very near the deploying air bag.

Belts offer opportunity for setting high deployment velocity thresholds

Belt use can also provide the opportunity for setting higher deployment velocity thresholds. Since the belts provide sufficient protection in low-severity crashes, higher deployment thresholds, i.e., ΔV at which the air bag deploys, could be used for belted drivers.

7.3.6 Crash Pulse and ΔV . Crash pulse shape is extremely important, because it governs the occupant position and motion during the crash. The shape of the crash pulse depends on the car platform and the obstacle being struck. All air bag systems are designed and developed for specific vehicle platforms. For crash pulses with the same ΔV , those having a high early acceleration spike of significant duration will move the occupant forward faster than a softer crash having the same ΔV . A “hard” pulse puts the occupant closer to the air bag module earlier in the crash than does a softer crash pulse. To avoid inflation-induced injury, vehicles with hard pulses, such as utility vehicles, must have earlier air bag deployment.

Crash pulse shape affects occupant proximity to the air bag

The results of calibrated simulations that show dummy responses and injury risk as a function of vehicle velocity, i.e., ΔV during the crash, are shown in Figures F-6 through F-21 for fully powered and

Effect of crash plus and ΔV

depowered inflators, for rigid and generic crash pulses, for 5% female and 50% male occupants, and for belted and unbelted occupants. These simulations were performed with early deployment of the air bag, so the results do not reflect late deployment due to deployment time variability. Figure F-12 shows that neck injury risk for the 5% female remains very small with the depowered inflator at ΔV s from 24 km/h (15 mph) to 56 km/h (35 mph), while it is significant for the fully powered inflator. Figure F-20 shows that neck injury risk for the 50% male is not significant at any ΔV from 24 km/h (15 mph) to 56 km/h (35 mph).

Belt load risks

Figures F-13 and F-21 show that chest injury risk for both the 5% female and the 50% male is significant due to shoulder belt loading at ΔV s from 24 km/h (15 mph) to 56 km/h (35 mph). Advanced technology belts with load limiters offer potential to reduce chest injury risk due to belt loading.

7.3.7 Occupant Category. Smaller-statured drivers sit closer to the air bag module and are therefore at greater risk of inflation-induced injury. In addition, females and children are more susceptible to neck and chest injury than are adult males. Differences in occupant fragility are shown in the injury risk curves of Appendix E.

7.4 APPLICATION OF ADVANCED TECHNOLOGY

Process for evaluating advanced technologies

The technology characterization described in Section 5 and the injury risk analysis and sensitivities given in Sections 7.2 and 7.3 provide a basis from which to evaluate the performance of advanced air bag technologies. The application of advanced technology changes the knowledge or value of the critical parameters. This change in knowledge is used with the injury risk sensitivities and advanced technology application strategies to establish the change in injury risk, or air bag robustness, that advanced technology can provide. This process is shown in Figure 7-4.

Nontechnical strategies that can improve restraint system effectiveness and reduce injury risk are also shown in Figure 7-4. For example, strategies that increase safety belt or child safety seat use, or that ensure that children will be carried in the rear seat, will be highly effective in reducing fatalities and injuries in motor vehicle crashes. These strategies were not the subject of this assessment.

Technology evaluation options considered

Table 7-18 summarizes the advanced technologies applicable in a given vehicle model year,* the strategy for applying the technologies, the improvements in terms of reduced air bag injuries, and problems remaining after introduction of the advanced technology. The baseline

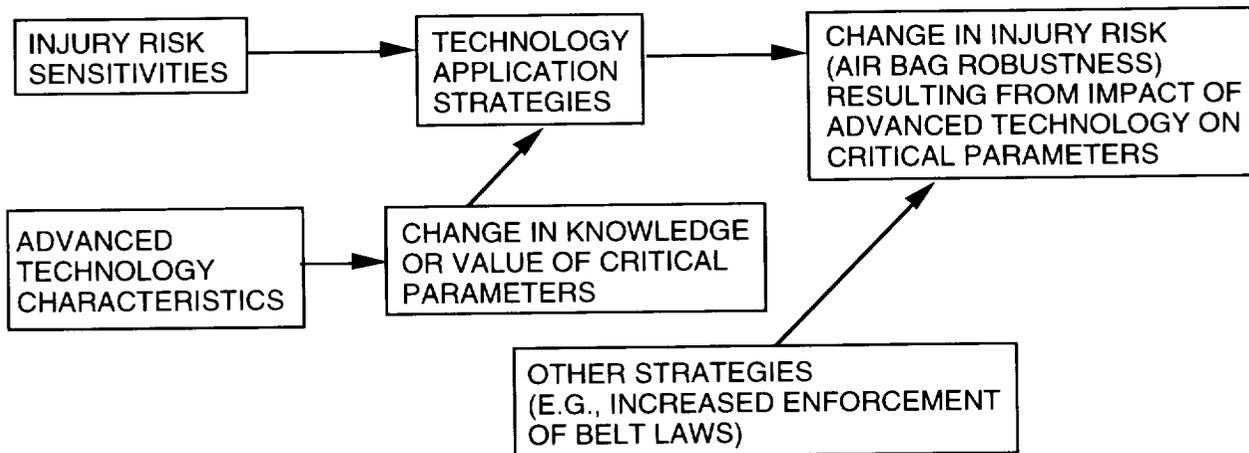


Figure 7-4. Advanced Technology Evaluation Process

for comparison is production air bag systems that were typical until manufacturers began to depower their systems. The first modification considered is the typical depowered system. Next are advanced technologies that could be introduced by model year 2001. Finally, we considered advanced technologies that might become available after about 2003.

7.4.1 Baseline Case. The baseline case indicates the risks to drivers and right front seat passengers in the majority of cars with air bags currently on the road. These include all out-of-position (OOP) occupants who are or will be within the keep-out zone. Static OOP occupants are within this keep-out zone, while dynamic OOP occupants will move within this region just before or during air bag inflation. Fifth-percentile female drivers are at risk. Front-seat passengers at risk are children, particularly those who are unrestrained or who are in rear-facing child safety seats (RFCSS). JPL had no data on the injury risk for children in forward-facing child seats (FFCSs), but we have assumed that they are at risk.

*Current system is baseline.
At-risk occupants identified*

7.4.2 Depowered Air Bags (Case 1). Depowered air bags were introduced in a few 1997 and many 1998 model vehicles to reduce inflation-induced injuries for 5th-percentile female drivers, and are expected to reduce the risk to all OOP front-seat occupants because of the reduction in the size of the keep-out zone. Although there was some evidence that normally seated 5% female drivers could be injured by depowered air bags (Section 7.3.3), it is assumed that

*Depowering reduces risk to
small-statured drivers*

* The model year for introduction of advanced technologies will be determined by the technologies' availability and the decisions of OEMs and suppliers to introduce them. The model year for introduction in Table 7-18 is an estimate of what is possible.

continued development will reduce that possibility. Front-seat occupants who are very close to the air bags, children and infants in RFCSS and FFCSs remain at severe risk with depowered bags.

7.4.3 Model Year 2001 (Case 2). The technologies that are being developed and that may be available for model year 2001 provide both improved information and improved response.

Information

- Crash sensors with improved algorithms that will better discriminate when air bag deployment is necessary for occupant crash protection, and can determine the appropriate inflation level for two-stage inflators.
- Belt status sensors that can detect when an occupant is belted so that the air bag deployment threshold can be raised when belts are in use. (This approach is currently in use in some cars.)
- Seat position sensors that provide an approximate surrogate measure of occupant size and proximity to the air bag module. They can be used in combination with belt status sensors to determine the appropriate inflator output.
- Seat belt spool-out sensors could provide additional information about an occupant's size and proximity to the air bag module. These sensors are not part of any current industry use strategy that JPL knows of, and therefore they may not be available by model year 2001.
- Static proximity (occupant position) sensors could identify occupants in the keep-out zone, but will be available only if an aggressive development program is undertaken. They would not reduce injuries to all OOP occupants, and they could be "fooled" some of the time.

Response

- Automatic suppression capability can respond when the system senses that an occupant is in the keep-out zone.
- Two-stage inflators permit relatively soft inflation for lower-velocity-threshold crashes and full inflation when necessary for high-velocity-threshold crashes.

Table 7-18. Reduction of Air-Bag-Induced Injuries with the Introduction of Advanced Technology

Time Frame	Applicable Technology	Strategy of Use	Improvements						Continued (and New) Problems(5)															
			Driver		Front-Seat Passengers		Driver		Front-Seat Passengers															
			Belted	Unbelted	Belted	Unbelted	Belted	Unbelted	Belted	Unbelted														
Present	Base case: Current system							OOP (S&D)(2) 5F	OOP (S&D)(2) 5F	OOP (S&D)(2) Child RFCS FFCS	OOP (S&D)(2) Child RFCS FFCS													
1998	1. Depowered Air Bag Information Crash severity Response Depowered air bag	Implement in all vehicles	OOP (1) 5F	OOP (1) 5F	OOP (1)	OOP (1)	OOP (1)	OOP (S&D)	OOP (S&D)	OOP (S&D) RFCS FFCS Child	OOP (S&D) RFCS FFCS Child													
2001	2. First Phase—Advanced Technology Information Crash severity (improved algorithm) Belt status Seat position Belt spool-out sensor Response 2-stage inflator Advanced belts pretensioners load limiters Advanced air bags	<ul style="list-style-type: none"> Use belt sensor to set higher threshold velocity for belted occupants (LT – Low Threshold, HT – High Threshold) Use seat position to determine inflator response – low or high Inflator response is: <table border="1" style="margin-left: 20px;"> <tr> <td>Seat Position</td> <td>Belted</td> <td>Unbelted</td> </tr> <tr> <td>F</td> <td>low (LT)</td> <td>low (LT)</td> </tr> <tr> <td>M</td> <td>low (HT)</td> <td>high (LT)</td> </tr> <tr> <td>R</td> <td>high (HT)</td> <td>high (LT)</td> </tr> </table> Low – lower than depowered High – higher than depowered, but lower than current systems Advanced belts limit proximity to air bag and control peak loads on occupants Advanced air bags reduce keep-out zone 	Seat Position	Belted	Unbelted	F	low (LT)	low (LT)	M	low (HT)	high (LT)	R	high (HT)	high (LT)	(A) OOP (3)	(B) OOP (3)	(A) OOP (3)	(B) OOP (3)	OOP (S&D)	OOP (S&D)	OOP (S&D)(6) RFCS FFCS Child	OOP (S&D)(6) RFCS FFCS Child		
Seat Position	Belted	Unbelted																						
F	low (LT)	low (LT)																						
M	low (HT)	high (LT)																						
R	high (HT)	high (LT)																						
	3. First Phase—Advanced Technology (Aggressive Development) Same as 2, except add suppression capability and replace seat position sensor with static proximity sensor	Same as 2, except use proximity sensor to determine inflator response and suppress if occupant is in static keep-out zone	OOP (S)	OOP (S)	OOP (S)	OOP (S)	OOP (S)	OOP (D)	OOP (D)	OOP (D) RFCS FFCS Child	OOP (D) RFCS FFCS Child													
~2003	4. Second Phase—Advanced Technology Same as 3, except replace static proximity sensor with a static and dynamic proximity sensor and an occupant sensor. Add precrash sensor.	<ul style="list-style-type: none"> Use belt sensor to set higher threshold velocity for belt occupants Use occupant and proximity sensors to determine inflator response Use proximity sensor to suppress when in static and dynamic keep out zone Use precrash sensor to augment crash sensor to reduce delayed deployments 	Full protection against air-bag-induced injuries				OOP (4)	OOP (4)	OOP (4)	OOP (4)	OOP (4)	OOP (4)												
2001	5. Advanced belts – 4-point harness – Air belt – etc.	<ul style="list-style-type: none"> For all occupants who use belts Belts restrain occupants, including head, from impacting interior 	Full protection	No protection	Full protection	No protection	Full protection	None	None	All	None	All												

(1) OOP injuries reduced due to reduced keep-out zone
(2) OOP (S&D) – static and dynamic out of position
(3) OOP injuries reduced further by further reduction in keep-out zone
(4) Unintended deployments due to unreliability
(5) This table is limited to reduction of inflation-induced injuries. For effects on protection see Section 7.4.8.

- Compartmented air bags and bags with lighter-weight fabrics that may reduce the size of the keep-out zone.
- Advanced belts can improve restraint system safety and protectiveness. They may include pretensioners that can provide better coupling of the occupant to the seat for improved ride-down during the crash. Also, they can, to some degree, limit occupant proximity to the air bag module. Load limiters can also improve belt performance by reducing maximum belt loads on the occupant. (Pretensioners and load limiters are currently in use in some vehicles).

Technology available by 2001 will provide marginal improvements over depowering

The application of advanced technologies in the 2001 time frame will reduce the size of the keep-out zone, which reduces the risk to front-seat OOP occupants. The inflation-induced injury risk to belted occupants with these systems will be reduced because of reduced air bag aggressivity, an increase in the threshold velocity for deployment, and improvements in belts. The inflation-induced injury risk to unbelted occupants will be reduced by the improvements that reduce air bag aggressivity, e.g., controlled inflator output, compartmented bags, and improved bag deployment design.

Despite these improvements, some front-seat OOP occupants, children and infants in RFCs and FFCs in the front passenger seat remain at risk.

Belt extension sensors, in combination with seat position sensors, could provide marginal improvement by 2001 by providing an indication of occupant size and proximity to the air bag module. However, there is no current OEM strategy known to JPL for use of belt extension or spool-out sensors. Nevertheless, OOP occupants would still be at some risk.

7.4.4 Model Year 2001 (Aggressive Development–Case 3). It might be possible to include a static proximity sensor in air bag systems by model year 2001. This would require an aggressive development program. The sensor would not have the capability of making dynamic proximity measurements, and could be “fooled” under some circumstances. In the event the sensor is fooled, air bag protection would be denied. Nevertheless, such a sensor could reduce inflation-induced risks to OOP front-seat occupants who are in the keep-out zone at the onset of a crash. Those who would remain at risk of inflation-induced injury include occupants who move into the keep-out zone in the early phase of the crash, infants in RFCs and FFCs, and child passengers in the front passenger seat.

Occupant and proximity sensors are needed to reduce air-bag-induced injuries

7.4.5 Model Year 2003 (Case 4). Further advanced technologies that could be incorporated by about the 2003 model year include more sophisticated integration of proximity and occupant position sensors with crash and belt status sensors. The system could then suppress inflation when it has a high likelihood of injuring an occupant in the keep-out zone and provide an appropriate signal for multistage inflators. Further advances in belt and air bag design could be introduced in this time frame. Also, precrash sensors could be available to augment crash sensors.

Unreliability remains a problem

With these more complex technologies, a risk of inflation-induced injury could result from system unreliability, unless diligent and productive effort is put into increasing the reliability of individual components to levels required to achieve satisfactory system reliability with the increased complexity of the system. As discussed in Section 4, the component reliability required to avoid unintended deployments, which could put all occupants at risk, is extremely high.

Initiate restraint design process with belts

7.4.6 Advanced Belts (Case 5). This case was added to illustrate a potential development effort, rather than to definitively establish the capabilities of advanced belts to provide protection. Since no air bag is used, there are clearly no inflation-induced injuries. The protective capability of advanced belts has not been determined. Neither has there been any belt-emphasized approach put forward in the U.S., because of the mandate to use air bags. Advanced belts alone may be the best choice for occupants who always wear their belts. Alternatively, advanced belts for belted occupants with an air bag for head protection could be a better choice. The head protection air bag could also provide protection to unbelted occupants through bag design and inflator control. The key consideration is to start the design process with belts and then determine what supplemental protection by air bags is required. Such a strategy must be predicated on the realities of belt use in the U. S., however.

Tags for child seat detection

7.4.7 Child Seats. In the analysis above, the resolution of the child seat problem is projected to be achieved in the 2003 time period or after. This is based on the requirement for implementation of reliable occupant presence sensors. One manufacturer (Mercedes-Benz) currently provides a tag-based child seat detector that automatically suppresses the air bag. Such a system could be used in other vehicles, but it must be used with specific tags attached to the seats. The problem of applying these tags to the different seats being offered and retrofitting them to older seats creates significant potential for misuse. The introduction of such a system would have to be carefully controlled.

7.4.8 Increased Protectiveness. During this assessment, the evaluation of the capability of advanced technology to increase the protectiveness of the occupant protection system was a secondary priority to reduction of inflation-induced injuries. However, the following observations can be made.

Depowered air bags will reduce the inflation-induced injuries for small-statured and fragile adults. However, they may also reduce the protectiveness of air bag systems for very large occupants and occupants in high-severity crashes, but JPL had no data to assess this premise quantitatively.

Effect of air bag suppression

Strategies used to reduce air-bag inflation-induced injuries include suppression of air-bag deployment. Clearly, strategies used to reduce air-bag inflation-induced injuries that result in the suppression of the air bag leave occupants unprotected if they are unbelted. The reduction in protectiveness resulting from these suppression strategies was not evaluated by JPL.

Dual inflators offer the potential for improved protection

Technologies that are expected to be implemented in model year 2001 have the potential for increasing air bag protectiveness by providing improved sensing that permits an improved air bag response. The capability that sensors provide permits the use of dual-stage inflators that will offer increased protection to large adults and occupants in high-severity crashes when compared to depowered air bags. The higher-level inflator stage offers that increased protection. Advanced safety belts will provide increased protection by better coupling of occupants to the vehicle (pretensioners) and reducing deceleration loads (load limiters).

In model year 2003 protectiveness will be increased further by refinements in the air bag response capabilities and additional safety belt improvements.

Effect of system unreliability

System unreliability will result in unintended nondeployments and occupants will be unprotected. Based on projected air bag installations and expected 0.9999 to 0.99999 system reliability, the number of unintended nondeployments will be in the tens per year. High system reliability is achievable through diligent effort; the actual number of unintended nondeployments will depend on the effort made to achieve high reliability.

In an advanced restraint system the desired air bag system response will be tailored to perceived occupant and crash attributes in an attempt to enhance the safety and protection afforded by the air bag. However,

Effect of complexity and crash prediction

this more complex decision structure creates additional categories of incorrect air bag system response, e.g., deployment may be desired in a given crash and the air bag deploys, but deployment is tailored to the wrong response state due to misperceived occupant/crash attributes.

Crash attributes may be the most difficult to reliably perceive, since they are necessarily a prediction of an extremely stochastic event whose attributes are generated during the event. To the extent that perceived occupant/crash attributes produce a different tailored response from the true attributes, air bag safety and protection can be adversely affected. Even ignoring economic issues, it is a major challenge to create a crash prediction system that is sufficiently accurate to be relied on for tailored air bag response.

SECTION 8—ADVANCED TECHNOLOGY DEVELOPMENT: NEEDS AND IMPLEMENTATION

8.1 OCCUPANT CRASH PROTECTION RESEARCH AND DEVELOPMENT

Research is a fundamental comprehensive inquiry into the nature of a subject, whereas development is a response to a problem or challenge. Development also extends research findings into practice, often while pursuing a particular approach, concept, or technology. The product of research is knowledge, while the product of development is the answer to a problem or need. Development sometimes raises questions that can best be addressed by further research. Benchmarking is a process of assessing or investigating the performance of particular concepts, technologies, or designs that result from a development program. JPL does not regard benchmarking as either research or development.

*Emphasis on benchmarking,
not R&D*

NHTSA and the automobile manufacturers are conducting a number of development activities pertaining to occupant crash protection. However, they are not conducting significant basic research, except in biomechanics. They are developing near-term responses to the challenges presented by injuries being inflicted by current restraint systems and are benchmarking existing and proposed technologies to address these challenges.

*Suppliers lead in technology
development*

OEMs are increasingly relying on suppliers to develop and propose technological approaches for improved restraint systems. JPL found that the bulk of development in occupant crash protection is conducted by the supplier industry. In keeping with this trend, we found that suppliers had most of the technical expertise in this field. Their expertise has been built up within their companies as well as through collaboration and joint ventures. The suppliers' capabilities were not comprehensive, however; they rely, for example, on NHTSA and the OEMs for biomechanical expertise.

Need to set requirements

Although suppliers are currently conducting the bulk of advanced restraint technology development, their work can lack the technical direction that comes from an overall systems perspective and that is critical to finding robust solutions to the problems with air bags. An incomplete understanding of a technological problem and performance requirements at an early stage of development is likely to lead to less than optimal performance from the developed

*NHTSA, OEMs and suppliers
need to cooperate to develop
performance goals*

technology. It can also make the development process inefficient and excessively time-consuming.

JPL believes that this situation impedes the development of advanced technologies for occupant crash protection. The challenge is to find a way that NHTSA, the OEMs, and suppliers can work efficiently together to define problems and determine complete and quantifiable performance goals and requirements. The requirements would provide the underpinning for improved and more comprehensive research and development. We believe that this process is necessary to produce robust occupant crash protection for new motor vehicles—restraint systems that are safe and effective in the full spectrum of automotive use and misuse.

The current governmental and private environment has not been optimal for this process. The history of air bag development, attitudes within both industry and government, and public concern about air bag safety present a less than ideal climate for such a program. We believe that it is critical to initiate a comprehensive research program to answer basic questions underlying occupant crash protection. This program should be coordinated between government and industry, possibly along the lines of the Partnership for a New Generation of Vehicles (PNGV). The results of this program should be in the public domain to support optimal restraint system development. Well-directed development programs, some of which may be proprietary, are equally critical to ensure that the next generation of occupant restraints will provide good protection without introducing hazards of their own.

8.2 DEVELOPMENT NEEDS

The concept that a public health measure be safe and effective is well established in medicine. It is less of a consideration in the field of automotive transportation. Occupant restraints must provide protection from the harm of crash forces (effectiveness) while not inflicting significant harm themselves (safety). A restraint should not exacerbate harm in a crash where restraint protection is needed, nor should a restraint cause harm in minor crashes or in the absence of crashes.

*Technology development is
needed to provide a robust
system*

Because of the very wide variety of normal operating conditions and of crashes of motor vehicles, a restraint system must be robust. That is, it must be reasonably safe under the full spectrum of vehicle operations and crashes while providing protection in the specific subset of crashes for which it is intended. To the extent that a restraint system causes or exacerbates injury, that performance may have to

be accepted for a time as a reasonable cost of the greater protection provided by the restraint. For example, people accept the risk of bruises and possibly broken clavicles from safety belts in a crash as a reasonable cost of their protection. Significant numbers of deaths and serious injuries—particularly to children—are not generally accepted.

As a consequent of our inquiry into air bag technology and performance, we have been convinced that improvement in the robustness of air bags is feasible. An orderly process would begin with a comprehensive research and development program into the challenge of occupant crash protection. In the current climate, which is demanding immediate results, it is probably unrealistic to expect such a program. It is critical, however, that the industry conduct additional development and comprehensive testing to fully evaluate new technological concepts. In this section, we outline what we believe to be the critical developmental challenges.

8.2.1 Deployment Time. Minimizing deployment time is critical to robust air bag performance. The time from the outset of a crash to full inflation has three phases. The first and most critical is the time to sense that a crash of sufficient severity is occurring. For most crashes, this is 10 to 15 ms, but it can be substantially longer. The second is the time to send a signal to the inflator and precipitate ignition. This is only 2 to 3 ms and probably needs little further attention, except for cold temperature effects. The third is the time for actual bag inflation, which is typically 30 ms for current systems. This time is not affected by the type of crash or other external factors but may vary because of inconsistent performance among inflators.

Deployment time elements

Effective bag inflation time may be reduced by the introduction of new bag designs, such as those that deploy radially or that use compartments or variable venting. These designs may permit occupant interaction in less than 30 ms and with smaller keep-out zones.

For the near term, developers need to investigate the maximum time available for air bag deployment before occupant injury (from the bag or from the crash) becomes likely in a given vehicle for the spectrum of crashes and determine the effect of applying advanced air bag designs on the deployment time. For the longer term, it is desirable to develop air bags and vehicle interiors that virtually eliminate air bag inflation-induced injuries.

New bag designs merit development effort

The effectiveness of new crash sensor algorithms needs evaluation

Crash sensors predict crash severity. Some current industry development programs are aimed at improving crash sensor algorithms. The effectiveness of these improvements will have to be evaluated. Precrash sensing has the potential to reduce deployment time. The discussion of precrash sensing in Sections 4 and 5 revealed a number of unanswered questions about its applicability that need to be addressed. Finally, what does the stochastic nature of the crash environment tell us about the limitations of crash severity prediction?

Occupant and proximity sensors are key to reducing air-bag-induced injuries

8.2.2 Occupant and Proximity Sensing. Our evaluation of occupant and proximity sensing showed them to be key to reducing air-bag-induced injuries. Current development programs do not appear to be sufficient to support the introduction of either occupant or dynamic proximity sensors by model year 2001. JPL believes that accelerated development of these sensors is warranted.

Inflator variability must be reduced

8.2.3 Control of Air Bag Inflation. Controllable air bag response depends on having an inflator that can be staged. Staged inflators have been developed (and were, in fact, part of the first commercially produced air bags). Unfortunately, inflator variability may overwhelm the capability to effectively stage the systems. The current level of inflator variability is unacceptable, in our view. Variability must be addressed as part of the development of staged inflator systems.

Safety belts can and should be improved; air belts should be evaluated and provided as an option

8.2.4 Safety Belt Systems. Advanced safety belt systems development has not received the emphasis it deserves, possibly because of the focus on air bag development. Pretensioners and load limiters have been installed in a small number of mostly European vehicles, and there are plans by various OEMs to expand their installation. Advanced safety belt systems merit increased development effort. The large majority of drivers in cars with air bags wear safety belts, and they deserve the benefit of improved systems. The development efforts should include alternative belt designs, pretensioners, load limiters, and air belts. The possibility that a system with advanced belt designs and air belts could be designed to be more effective, and less injurious, than conventional air bags with three-point belts should be investigated.

High reliability is required

8.2.5 System Reliability. Based on our limited analysis of reliability, we found that very high system reliability is required to minimize the number of unintended deployments and nondeployments where air bags could reduce occupant crash injury. Even with the highest possible reliability these events will occur. They could result in significant injury under certain circumstances. Vehicle manufacturers and their suppliers must continue to make high

reliability a high priority in design, manufacturing, and maintenance programs.

8.3 DATA NEEDS

Our assessment found a paucity of publicly available data from which to evaluate air bag system performance. Two types of data that are critical to evaluation were lacking. First, there is a critical lack of real-world crash data for vehicles with air bags from which to determine the performance of air bag systems and to diagnose the full nature and extent of inflation-induced injuries. Second, test protocols for air bag systems available to JPL are inadequate to evaluate the effectiveness and safety of these systems. The consequence is that we lack adequate information on the performance of systems currently being produced as well as on the performance of advanced air bag technologies.

Need for better real-world crash data

8.3.1 Real-World Crash Data. It was revealed early in this study that insufficient data exist on real-world experience with air bags. In particular, the existing crash data were insufficient to support an engineering assessment of this technology. One of the principal uses of a crash data base in an engineering analysis of restraint systems might be to establish the important variables influencing injury under diverse scenarios.

Malliaris, in a current effort for the AAMA [10], has shown that the National Automotive Sampling System (NASS) data base cannot support such a study at the detailed level required for a comprehensive engineering analysis. In part, that is a consequence of NASS funding, which is now much lower than originally planned to meet desired coverage and precision levels. In a stratified sampling plan such as NASS, sample size, and hence funding needed to run the system, are derived from the coverage and precision requirements. Underfunding results in an inability to use the database to answer the kinds of detailed questions essential to guiding an engineering analysis.

We believe that only the federal government is capable of conducting a comprehensive crash investigation and data collection program. At minimum, NHTSA should expand NASS to its original size, with full funding to conduct roughly 18,000 crash investigations annually. However, since it has been nearly 20 years since NASS was originally designed, JPL recommends that NHTSA revisit the question of how NASS should be structured and what procedures it should use before expanding it.

NHTSA should expand NASS

We also recommend that data collection in at least a substantial subset of cases in the Fatality Analysis Reporting System (FARS) be expanded. The additional data should approach the comprehensiveness of NASS cases.

The feasibility of crash detection using recorders with single-point sensing should be determined

Another source of real-world data may be available. The crash sensors in most current production vehicles use some kind of single-point accelerometer that lends itself to crash data recording. OEMs now use these systems in fleet test programs and in some production vehicles to evaluate air bag systems. If most new vehicles were fitted with data recording devices from which key data could be obtained, it would provide a very valuable source of data for analysis. This could improve our understanding of real-world crashes and the conditions for which air bags must be designed. The development of a low-cost crash recording device is technologically feasible, but the institutional problems, such as data collection, ownership, and privacy would have to be resolved before such a program was initiated.

These recorders could serve other purposes also, such as emergency rescues where their information could be combined with occupant smart keys to provide critical crash and personal data to paramedics.

8.3.2 Test Protocols, Procedures, and Requirements Needs.

Improved test protocols and modeling are required

Further protocols and procedures for testing air bag systems need to be developed that provide the assurance of air bag system robustness. Statistical test methods can be and should be applied to develop test matrices that provide an adequate picture of air bag performance. Minimal data and modeling requirements to support the engineering analysis of restraint technology are:

1. A comprehensive data base for establishing engineering properties, variability, and reliability of restraint system components.
2. A comprehensive crash test/simulation program capable of supporting the evaluation of crash protection alternatives relevant for the exposure of the population at risk.
3. Consensus risk models (not necessarily simple parametric curves) that translate physical parameters into bodily insult for the population at risk.

Three fundamental questions are: (1) How should such test protocols and procedures be developed? (2) What mechanisms should be employed to make sure that these tests are used to ensure that

production restraint systems are both safe and effective? and (3) What provision should be made for dispensing the information to the public? JPL believes that industry, government, and others with interest and expertise in the subject can and should all contribute to these activities.

Both the public and the automotive industry (OEMs and suppliers) have a critical interest in ensuring that there is a broad consensus on which tests are necessary to produce occupant restraint systems that are safe and effective. They also have an interest in ensuring that such tests are conducted on all systems provided for sale to the public and that performance under these tests meets reasonable minimum levels appropriate for public safety. We do not believe that a federal regulatory program alone can achieve these ends, even with full public participation in rule-making that is used for the development and adoption of regulatory requirements.

While the basic requirements of FMVSS 208 are critical to ensuring that new motor vehicles provide a minimum level of occupant crash protection, we do not believe it is feasible to incorporate the full spectrum or matrix of test requirements in that standard. Thus, a program to supplement the requirements of FMVSS 208, which may include a limited expanded test requirement, should be considered.

The mechanisms to be used would have to be acceptable to the government and industry participants, and operate within their regulatory and competitive environments. Organizations such as the Society of Automotive Engineers (SAE) and the American Society for Testing and Materials (ASTM) could play key roles. They have long and distinguished histories in the development of recommended practices and technical standards of the type needed in this instance. Note that a federal government standards acceleration program is under way by the Intelligent Transportation System Joint Program Office of the U.S. DOT. That program may be a model for this recommended activity.

SECTION 9—CONCLUSIONS

1. The injuries and fatalities resulting from air bag deployments are symptoms of underlying problems in designing air bags for a broad spectrum of crash types and severities. Air bags are a significant engineering design challenge because they deploy rapidly and with great force toward an approaching occupant. Their deployments are based on predictions of the crash severity early in the event, where the crash environment is highly variable. Also, air bag system response is variable.
2. There is little evidence that air bag performance has been fully characterized, i.e., that air bag capabilities and deficiencies are fully known. Such capabilities and deficiencies are not available in the open literature or from NHTSA. If any of the air bag suppliers or OEMs have developed such a systematic characterization, it was not made available to JPL when requested.
3. Air bags cause injury if an occupant is in close proximity to them when they deploy. The region of high injury risk is defined by a keep-out zone. As long as air bags are capable of causing injury, there will be a keep-out zone. Injury risk will continue until the keep-out zone is eliminated by technology or design, or if the air bag is disabled when an occupant is within it. Of course, if an air bag is disabled, it will not provide protection.
4. The development of advanced restraint systems is influenced by government regulatory requirements and industrial cost issues. Because of the nature of the regulatory process and the industrial technology implementation process, the resulting air bag systems may not achieve optimum safety or be introduced in the most timely way.
5. Advanced technology can improve the safety of air bag systems by providing (1) more information about the crash, and (2) a better restraint response that is tailored to the individual occupants. Improving air bag safety is an incremental process, and implementation of advanced technology will be evolutionary. The following improvements can be expected, but data will be required to confirm the projection.

(The projections in paragraphs 5b and 5c are based on limited contacts with a limited number of vehicle manufacturers and suppliers. The state of the art of advanced air bag technologies

is in a high state of flux, and the technologies discussed in this report, as well as others, may advance more or less rapidly than indicated.)

- a. At present, depowered air bags will greatly reduce the air-bag-induced injury risk to normally seated, small-statured drivers. Also, these air bags will reduce the “keep-out” zone, where deploying air bags can injure out-of-position front-seat occupants. Thus, fewer of these occupants will be at severe risk. Remaining at risk of air-bag-induced injury are the front-seat occupants who are still out of position within the new keep-out zone as well as children and infants in rear-facing child seats (RFCSs) and forward-facing child seats (FFCSs) in the right front passenger seat.
- b. By model year 2001, advanced technologies such as improved crash sensors, belt-use sensors, seat-position sensors, automatic suppression, two-stage inflators, compartmented air bags, pretensioners, and possibly seat belt spool-out sensors and static proximity sensors will be available. Compared to depowered air bags, the application of advanced technologies in model year 2001 will further reduce the size of the keep-out zone, which in turn reduces the risk to out-of-position (OOP) front-seat occupants. This reduction will be due to less aggressive air bag response—a result of improved air bag design and dual inflators that provide more tailored responses. The risks to belted front-seat occupants with these second-generation systems will be reduced not only because of diminished air bag aggressivity, but also because of an increase in the threshold velocity for deployment, and improvements in belts. The risk to unbelted front-seat occupants will be similarly reduced by the changes in air bag performance. Despite these improvements, some OOP occupants will remain at severe risk from deploying air bags, as will children and infants in RFCSs and FFCSs in the right front passenger seat.
- c. For model year 2003, more sophisticated integration of proximity and occupant position sensors could be incorporated. The system could then suppress inflation when it has a high likelihood of injuring a front-seat occupant in the keep-out zone and provide an appropriate signal for multistage inflators. Further advances in belt

and air bag design could be introduced in this time frame. With these technologies, the only serious risk of air-bag-induced injuries would come from the unreliability of the system. System unreliabilities are expected to result in tens to hundreds of unintended deployments per year. These unintended deployments could have the potential of causing a few injuries per year.

6. During this assessment, evaluating the capability of advanced technology to increase the protectiveness of air bag systems was a secondary priority. However, the following observations can be made:
 - a. Depowered air bags may reduce the protectiveness of air bag systems for very large occupants and occupants in high-severity crashes, but JPL had no data to assess this premise.
 - b. Strategies used to reduce air-bag-induced injuries include suppression of the air bag deployment. Clearly, strategies used to reduce air-bag-induced injuries that result in the suppression of the air bag leave occupants unprotected if they are unbelted.
 - c. Technologies that are expected to be implemented, beginning in model year 2001, have the potential for increasing air bag protectiveness by providing improved sensing and improved air bag response. Sensors permit the use of dual inflators that will offer increased protection to large adults and occupants in high-severity crashes when compared to depowered air bags.

7. The above expected improvements in safety and protectiveness of air bags must be tempered by the understanding that there are key technology development needs to be overcome, namely:
 - a. Air bag deployment time variability must be reduced by improvements in the vehicle crush/crash sensor system.
 - b. Inflator variability must be reduced so that dual-stage inflators can be applied effectively.
 - c. System and component reliability must receive diligent attention to achieve the high levels required under field conditions.

- d. Occupant sensors must be developed that can distinguish with high accuracy small, medium, and large adults; children; and infant seats.
- e. Position sensors to measure occupant proximity to the air bag module with the required response time and accuracy must be demonstrated.

All of the above are the subject of current development, but development, test, and integration of the advanced technologies needs to be accelerated to enable its incorporation into production vehicles.

- 8. There are many generic capabilities within NASA that could be applied to air bag development. These include sensors, computing, control systems, neural networks, algorithm development, microelectronics, simulations, propellants, propulsion, and inflatable systems. NASA's systems analysis and engineering capabilities could also be applied to a number of problems such as assessing air bag performance, developing a test program to evaluate effects of variability of critical parameters on air bag performance, and applying defect detection and prevention methodologies to enhance reliability. We identified some specific technologies that could be applied to advanced air bags, including two sensors that suppliers are currently evaluating. These are a capacitive sensor for proximity sensing and a stereoscopic vision system for proximity or precrash sensing.
- 9. Safety belts are the primary and most effective occupant restraint system, and they are used by a large majority of occupants. Safety and protection for belted occupants is likely to be substantially enhanced if advanced air bag designs can be predicated on the use of advanced safety belts, and not compromised by accommodation for protection of unbelted occupants. The growing use of safety belts may permit such a design strategy.
- 10. When specific technology is mandated, the mandate can impede the development of alternative, possibly superior, technologies. Specific advanced restraint system technology should not be mandated.
- 11. The application of technology is often thought to be the solution to today's problems. This assessment concluded that advanced

technology can make air bags safer and more protective. These air bag improvements are important and significant, and should be implemented. However, the improvements that will result from advanced technology applications are small compared to safety improvements that could be achieved through changes in driver behavior, such as increased safety belt use, reduced drunk driving and aggressive driving, which have been documented to be major causes of crashes.

SECTION 10—RECOMMENDATIONS

Recommendations are directed to NHTSA and industry, including actions that require their cooperation.

10.1 NHTSA

10.1.1 The Need for a Better Understanding of Restraint System Performance. This assessment revealed activities that will require further study. Also, data required to conduct important analyses were not available to JPL. As a consequence, JPL recommends the activities described below:

- (1) Continue restraint system assessment, with emphasis on restraint protection, and include consideration of costs and benefits.
- (2) Evaluate and quantify, to the extent possible, the benefits of the application of advanced technology to improve safety and protection of restraint systems with respect to injury risk of the full spectrum of occupants in the full range of crash severities experienced by the public. The benefits, costs and risks of advanced technology should be investigated and understood with respect to injury to head, neck, chest, and other body regions across the full range of occupant categories and crash severities.
- (3) Expand the assessment of advanced technology to crashes other than the frontal crashes that were the focus of this assessment.
- (4) Develop a systematic vehicle test protocol that (a) incorporates measurements for comprehensive injury risk evaluation (head, neck, chest, etc.) for the 5th-percentile female, 50th-percentile male, and 95th-percentile male drivers as well as the full spectrum of passengers, and (b) includes crash severities representative of the full range of “real-world” collisions.
- (5) Evaluate the impact on air bag performance of deployment time variability, inflator variability and system and component reliability for any advanced technology. Again, the full range of occupant size and crash severity that represent use by the general public must be considered.

10.1.2 The Need for Better Real-World Data. The recommendations that follow result from the deficiencies of the real-world data that are available for diagnosis of safety problems or the

support of safety engineering analyses. These data were insufficient for use in this assessment. Efforts should be undertaken to:

- (6) Expand the National Automotive Sampling System (NASS) and revisit the question of how it should be structured and what procedures should be used to provide data needed for safety diagnosis and engineering analysis.
- (7) Study the feasibility of installing and obtaining crash data for safety analyses from crash recorders on vehicles. Crash recorders exist already on some vehicles with electronic air bag sensors, but the data recorded are determined by the OEMs. These recorders could be the basis for an evolving data-recording capability that could be expanded to serve other purposes, such as in emergency rescues, where their information could be combined with occupant smart keys to provide critical crash and personal data to paramedics. The questions of data ownership and data protection would have to be resolved, however. Where data ownership concerns arise, consultation with experts in the aviation community regarding the use of aircraft flight recorder data is recommended.

10.1.3 The Need for a Better Understanding of the Future Potential of Technology. NHTSA is routinely briefed by suppliers and OEMs on the development of advanced technology and conducts independent evaluations of important advanced technologies. We therefore recommend that NHTSA:

- (8) Evaluate specific technologies that have promise of significant safety benefit, such as:
 - Precrash sensors—both separately and coupled with the crash-avoidance sensors now being investigated—which could provide improved crash type and severity sensing
 - Advanced belt systems and air belts that could improve protection, but have been neglected because of the emphasis on air bags
 - Air bag/inflator designs that could eliminate the keep-out zone and the information (sensors) required to support the functioning of the design

10.2 THE NEED FOR CONTINUED ADVANCED TECHNOLOGY DEVELOPMENT BY INDUSTRY

It is industry's responsibility to provide safe and protective vehicle restraint systems, and to develop the technology to provide these systems. We recommend that industry:

- (9) Continue diligent efforts to implement the advanced technologies that have been shown to JPL, because those technologies will make restraint systems safer and more protective.
- (10) Reduce the deployment time and inflator mass flow variabilities; otherwise these variabilities will have detrimental effects on advanced air bag system effectiveness.
- (11) Continue diligent efforts to increase restraint system reliability.

10.3 NHTSA/INDUSTRY COOPERATIVE EFFORTS

- (12) Develop quantitative goals for safer and more protective restraint systems that address air-bag-induced injuries and protection in high-severity crashes.
- (13) Continue to develop and refine biomechanical injury criteria for restraint systems using the best science available.
- (14) Develop protocols and procedures for testing air bag systems to ensure air bag system robustness.
- (15) Inform the public of the specific risks associated with each vehicle air bag, e.g., by providing the keep-out zone dimensions, and recommend ways to mitigate the risk.

APPENDIX A—ORGANIZATIONS CONTACTED

APPENDIX A—ORGANIZATIONS CONTACTED

The following is a list of the organizations that were in contact with JPL.

A.1 ORIGINAL EQUIPMENT MANUFACTURERS (OEMs)

- American Honda Motor Co., Inc.
- American Suzuki Motor Corporation
- Chrysler Corporation
- Ford Motor Company
- General Motors Corporation
- Mercedes-Benz of North America
- Nissan North America, Inc.

A.2 COMPONENT SUPPLIERS

- Ad Astram Technologies, Inc.
- Advanced Safety Concepts, Inc.
- AirBelt Systems
- Allied Signal Corporation
- ASD Simula
- AutoLiv Corporation
- Automotive Systems Laboratory, Inc./Takata
- Automotive Technologies International, Inc.
- Breed Technologies, Inc.
- Computer Application Systems, Inc.
- Delco Electronics, Inc.
- Delphi Automotive Systems
- Header Products, Inc.
- Hittite Microwave Corporation
- Johnson Controls, Inc.
- Mentor Technologies, Inc.
- Morton International (Autoliv)
- Narricot Industries, Inc.
- NEC Technologies, Inc.
- Petri, Inc.
- Precision Fabrics Group, Inc.
- Robert Bosch Corporation
- TRW
- Universal Propulsion Company, Inc./Talley Industries
- William Lear Corporation

A.3 ASSOCIATIONS

AAMA
AIAM
Farmers Insurance Co.
Insurance Institute for Highway Safety
USCAR

A.4 GOVERNMENT AGENCIES

NASA Centers
NHTSA
Sandia National Laboratories
Transport Canada
Volpe Transportation Systems Center

APPENDIX B—QUESTIONNAIRE

APPENDIX B—ADVANCED AIR BAG TECHNOLOGY SURVEY

QUESTIONNAIRE

This questionnaire has been developed to apply to all aspects of occupant protection. Select and respond only to those questions relevant to your technology. Provide test data where possible. Specific answers to the questions are requested; see the example attached. If answers to the questions do not provide all the relevant information about your technology, please provide additional information. If information is proprietary, JPL can protect it and can sign nondisclosure agreements. It is requested that all questionnaires be returned no later than September 5, 1997. Please return the questionnaire to:

Robert L. Phen
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109

Fax: (818) 354-8453
Email: robert.l.phen@jpl.nasa.gov
For questions call: (818) 354-3453

A. TECHNOLOGY SUPPLIER INFORMATION

Company Name _____

Address _____

Point of Contact _____

Phone/Fax _____

E-Mail _____

B. ADVANCED TECHNOLOGY TYPE

Check your technology development areas.

1. Precrash sensors
2. Crash severity sensors
3. Sensing diagnostic modules/Crash detection algorithms
4. Occupant type sensors
5. Occupant proximity/motion sensors
6. Computational systems/algorithms
7. Inflators
8. Air bags
9. Seat belt systems
10. Other primary restraint systems
11. Systems integration
 - a. Diagnostics (status) sensors
 - b. Other system integration sensors (define)
 - c. System integration computational systems/algorithms
 - d. Data communications/transfer
12. Other (define)

C. TECHNOLOGY DESCRIPTIONS AND PERFORMANCE

For each technology checked above, please provide the following data.

1. **Precrash sensors**
 - a. Description of system
 - b. Method for obstacle detection
 - Describe sensing method
 - Describe determination method/algorithm
 - c. Detectivity
 - Define ability to measure obstacle (type and size) at various ranges/closing speeds
 - Define response time, ranging resolution/accuracy, obstacle size threshold
 - d. Reliability – Describe
 - Failure modes
 - False positives/total number of trials not involving a significant obstacle
 - False negatives/total number of trials involving a significant obstacle
 - e. Description of other performance metrics/other performance data
 - f. Test methodologies
 - g. Output format (high-level identification, low-level data for external data acquisition systems, etc.)
 - h. Systems requirements for implementation in vehicle
 - i. Expected production costs
 - j. Current state of readiness
 - R&D
 - Developmental testing with OEM
 - Fleet testing

- k. Model year in which system would be ready for introduction.
- 2. Crash severity sensors**
- a. Description of sensor
 - b. Description of sensor placement in vehicle
 - c. Discrimination time and variability in discrimination time for the following tests (Feel free to quote vehicle specific times/variabilities)
 - 30-mph rigid fixed barrier (RFB)
 - 30-mph offset deformable barrier (ODB)
 - 35-mph+ RFB/ODB
 - AAMA sled pulse (if possible for sensor system)
 - 20-mph RFB/ODB
 - Minimum crash leading to air bag deployment
 - d. Description of algorithms, if applicable
 - e. Reliability – Describe
 - Failure modes
 - No deploy decisions/total number of trials deployable event
 - Deploy decisions/total number of trials involving nondeployable events
 - f. Systems requirements for implementation in vehicle
 - g. Expected production cost
 - h. Current state of readiness
 - R&D
 - Development testing with OEM
 - Fleet testing
 - i. Model year in which system would be ready for introduction
- 3. Sensing diagnostic modules/crash detection algorithms**
- a. Operational requirements of hardware and/or software
 - b. Hardware overview
 - c. Software overview
 - d. Specific fault-tolerance/fault-detection features
 - e. System processing time (update rate)
 - f. Reliability
 - Failure rates across large sample (define failure specification)
 - g. Test methodology
 - h. Describe data outputs to other vehicle systems
 - i. Describe data inputs to system
 - j. Systems requirements for implementation into vehicle
 - k. Expected production cost
 - l. Current state of readiness
 - R&D
 - Development testing with OEM
 - Fleet testing
 - m. Model year in which system would be ready for introduction

4. Occupant type sensors.

For each separate occupant type detector system, please address the following applicable occupant types when providing the performance information.

- Rear-facing infant seat
 - Front-facing child seat
 - Child passenger
 - Adult passenger
 - Adult driver
 - Occupant size/weight
 - Empty passenger seat
 - Inanimate object in passenger seat
- a. Detection principle
 - b. Ability to detect/distinguish occupant types
 - c. Detection accuracy and repeatability
 - d. Reliability
 - Current failure modes/confounding data
 - False positives/total number of trials not involving that type of occupant
 - False negatives/total number of trials involving that occupant
 - e. Methods to correct current problems; expected future performance
 - f. Description of other performance metrics/other performance data
 - g. Output format (high-level identification, low-level data for external data acquisition system, etc.)
 - h. Systems requirements for implementation in vehicle
 - i. Current state of readiness
 - R&D
 - Development testing with OEM
 - Fleet testing
 - j. Model year in which system would be ready for introduction

5. Occupant proximity/motion sensors.

For each separate sensor, please answer the following questions.

- a. Sensor type/detection principle
- b. Dimensionality (1-D range, 2-D, 3-D)
- c. Sensor location (IP headliner, seat, variable, etc.)
- d. Detection point(s) of occupant (surface or internal, point or curve, etc.)
- e. Speed/accuracy
 - Response time (e.g., response to 1/e for step input) for each measured direction
 - Measurement resolution/accuracy for that response time (for variable response time systems, variability of resolution/ accuracy with response time)
 - Testing method
- f. Description of other performance metrics/other performance data

- g. Reliability
 - Estimated variability of response time, resolution accuracy specifications across a large sample
 - Estimated failure rate across large sample (define failure specification)
- h. Output format (analog time series, digital time series, high-level indication, etc.)
- i. Systems requirements for implementation into vehicle
- j. Expected production cost
- k. Current state of readiness
 - R&D
 - Development testing with OEM
 - Fleet testing
- l. Model year in which system would be ready for introduction

6. Computational systems/algorithms.

For each system please address all of the points in section C.3 of this questionnaire

7. Inflators

- a. Design description
 - type of propellant
 - composition of evolved gases
 - temperature of evolved gases
 - time delay from inflator signal to full flow from inflator
 - mass flow rate versus time profile (show alternative for 2 + stage inflators)
 - duration of inflator operation
- b. Unique features of the design
- c. Performance variability of the design
 - unit-to-unit variability in rise rate
 - unit-to-unit variability in pressure level
 - unit-to-unit variability in flow rate
 - temperature sensitivity
 - element of the design that is responsible for the variability
- d. Reliability
 - failure modes
 - failure rate across a large sample (design failure specification)
- e. Current state of readiness
 - R&D
 - development testing with OEM
 - fleet testing
- f. Expected unit production cost
- g. Model year in which system would be ready for introduction

8. **Air bags**
 - a. Design description
 - bag material
 - porosity of material (venting capability)
 - fold pattern
 - tether design
 - bag volume, bag depth, bag surface area
 - vent area
 - b. Unique features of the design
 - c. Reliability
 - failure mode
 - failure rate across a large sample (define failure specification)
 - d. Current state of readiness
 - R&D
 - development testing with OEM
 - fleet testing
 - e. Expected production cost
 - f. Model year in which system would be ready for introduction

9. **Seat belt systems**
 - a. Design description
 - webbing material and design
 - attachment points for belts
 - retractor design
 - pretensioner (force levels, adjustability, response time).
 - load limiter (load, adjustability, response time)
 - automated operation?
 - status sensor systems?
 - b. Unique features of the design
 - c. Reliability
 - failure mode
 - failure rate across a large sample (define failure specification)
 - d. Current state of readiness
 - R&D
 - development testing with OEM
 - fleet testing
 - e. Expected unit production cost
 - f. Model year in which system would be ready for introduction

10. **Other primary restraint systems**
 - a. Design descriptions
 - b. Unique features of the design
 - c. Current state of readiness
 - R&D
 - development testing with OEM
 - fleet testing

- d. What is the expected unit production cost
- e. Model year in which system would be ready for introduction

11. Systems integration (e.g., diagnostics, computational systems/data communications/transfer)

- a. Description of technology
- b. Operations performed by technology
- c. Unique features of technology relative to that in current systems
- d. Performance (define performance metrics, and quantify system performance)
- e. Reliability (estimate variations in performance and failure rates across a large sample)
- f. Systems requirements for implementation into vehicle
- g. Expected performance costs
- h. Current state of readiness
 - R&D
 - development testing with OEM's
 - fleet testing
- i. Model year in which technology would be ready for introduction

12. Other

Describe salient features of the technology

SAMPLE RESPONSE (FICTITIOUS)

A. TECHNOLOGY SUPPLIER INFORMATION

Company Name: Crash Prediction Inc. (CPI)
Address: Detroit, MI

Point of Contact: James C. Maxwell
Phone/FAX (810) 333-3333/444-4444
Email delcrossB@CPI.com

B. ADVANCED TECHNOLOGY TYPE

XXX. 1. Precrash sensing

C. ADVANCED TECHNOLOGY DESCRIPTION AND PERFORMANCE

- a. The CPI precrash sensor is a two-antenna, radar system operating at 35 GHz. The right and left fender-mounted antennas allow for two separate ranging measurements

relative to each antenna at an update rate of 100 Hz. The far-field pattern of the two antennas overlap at a distance of 50 m, providing a near real-time indication of radar cross-section at a point 50 m in front of the vehicle. The system detects the instantaneous range of metallic/dielectric objects relative to both antennas. The sensing area is approximately 10m² (5 x 2 m centered with respect to the vehicles longitudinal axis and the top of the hood). The two independent antennas provide both redundancy and limited lateral resolution. The radar cross-section (determined by the amplitude of returned signals) allows for a determination of obstacle size. The radar signals are processed by a radar processing unit (RPU) integrated with each antenna. The RPU's output real-time range and size information. The range information from each antenna is combined and processed by a central data processing unit (CDPU) located in the occupant compartment. The CDPU outputs information on instantaneous range, closing velocity, and exact size to any of a number of air bag electronic control modules (ECM) currently used on vehicles. The sensor is capable of providing a reliable warning of an impending crash, as much as 5 seconds prior to collision.

- b. The CPI system uses transmission and reception of multiple mm-wavelength pulses. The pulses reflect off of objects in the field of view of the antennas. The round trip time of the pulses provides an accurate measure of range. The echo pulse amplitude provides an accurate measure of obstacle size and mass. The range information is differentiated to provide closing speed. The pulse amplitude information is similarly differentiated to allow estimation of the spatial distribution of the obstacle outside of the current field of view.
- c. The CPI system can detect metallic objects as small as 1 m², with a signal-to-noise ratio of 10:1, at an update rate of 100 Hz. The ranging resolution at this bandwidth is better than 1 mm. The accuracy is under 2 mm. The calculated closing speed resolution and accuracy are 0.1 m/s and 0.2 m/s, respectively.
- d. The total system reliability for the CPI sensing system is:
- 10 false positive signals of 3 m² or larger obstacle per 1 million trials not involving an obstacle.
 - 1 false negative signal in the presence of such an obstacle per 1 million trials

The reliability/unreliability is evenly distributed among the three subsystems (antenna, RPU and CDPU)

- e. CPI has defined an additional performance metric that relates sensor response to effective, relative permittivity of the obstacle. For a 1 m² obstacle with 100-Hz response time, the resolution accuracy vs relative permittivity are:

Relative perm.	Resolution/accuracy
10	0.1 m/0.2 m
20	0.05 m/0.1 m
50	1 mm/2 mm

- f. CPI tests its system only in stock vehicles on actual roads. The system response is logged, and the data is attached to a real-time stereo video record. The radar data is correlated with the video data off-line.
- g. The output format from the CDPU is an RS-488 message of time, range, closing velocity, and obstacle size.
- h. The radar antennas must be mounted on the exterior of each front fender. A 4- wire cable is routed from the CDPU (in the occupant compartment) to each antenna.
- i. The estimated production cost will be \$100.
- j. The CPI radar is in extended fleet testing with two American auto makers.
- k. The system will be ready for implementation in 1999 MY cars.

APPENDIX C—PROXIMITY SENSING

Appendix C—Proximity Sensing

C.1 USE OF PROXIMITY SENSORS

Proximity sensing has been proposed as a key component for an advanced air bag system designed to eliminate the inflation-induced injury (I³) problem. In its simplest form, the proximity sensor would be used to indicate that an occupant is dangerously close to an air bag module at the time a deployment decision is made. In this case the proximity sensor would provide data to a decision-making algorithm which, after weighing a number of factors, would control air bag deployment. Depending upon the form of the future air bag inflation system (single-stage, dual or multi-stage, continuously variable, etc.), the detection of an occupant in close proximity to an air bag module is generally expected to lead either to the deployment of an air bag at low inflation levels or to total suppression of the air bag. The proximity sensor might provide simple one-dimensional range information, i.e., scalar range between some portion of the occupant and the instrument panel (IP). However, more powerful techniques for two and three-dimensional ranging of multiple body points have been developed for proximity sensing applications.

The application of a proximity sensor has led to the concept of a “keep-out zone,” which defines a dangerous zone around an air bag module when the air bag is deploying. Present concepts for advanced air bag systems use this zone in the following manner:

- If *inside* this zone at the air bag deployment decision time, then either *suppress* the air bag or fire a depowered inflation stage.
- If *outside* this zone at the air bag deployment decision time, then, depending upon the status of other sensors, *deploy* the air bag.

At present, the deployment decision time is set by a crash severity sensing system which consists of one or more inertial sensors/switches in conjunction with a decision-making algorithm.

The earliest use of proximity sensors could be in a quasistatic mode, in which the sensor is used to suppress (or reduce) the air bag in response to a static out-of-position (OOP) occupant. Static OOP means that the occupant is within the keep-out zone for a length of time greater than or equal to the nominal crash pulse duration (on the order of 125 ms). Simply stated, an occupant that is “planted” within the keep-out zone for a time comparable to 125 ms will modulate (suppress or reduce) the air bag deployment. Consistent with this static application, many concepts for low-speed proximity sensing (response times 0.1 to 1 s) have been advanced. Often other information can be provided on this time scale, and technologies are under development that promise detection of, for example, occupant type (adult, small passenger/child, child seat, inanimate object), occupant size/mass, and occupant state (e.g., driver drowsiness).

As expected, applications for high-speed, dynamic proximity sensing have been envisioned. The physical process related to proximity sensing (ranging) would allow measurements to be made at ms or sub-ms rates with reasonable accuracy (absolute position determination) and resolution (minimum resolvable position difference).

Repeatability and reliability are key questions. Industry views using dynamic proximity information to improve the performance of advanced air bags by optimizing the restraint system for a wider range of occupant positions (more than just static OOP) and crash scenarios. In the ultimate case, a near real-time determination of occupant position with respect to in-cabin hazards may be an improvement over the current approach for crash sensing, in which the expected occupant motion is inferred from limited information related to the type and severity of the crash. This approach has been proposed by a number of groups.

From the following analysis, it can be seen that the extension from static sensing to dynamic proximity sensing carries with it some fundamental problems, particularly with unrestrained occupants. Specifically, dynamic proximity sensing applications cause enlargement of the keep-out zone and increased air bag suppression.

C.2 DYNAMIC OOP SENSING: ANALYSIS OF OCCUPANT KINEMATICS AND IMPLICATIONS FOR PROXIMITY SENSING

The analysis of occupant kinematics is intended to be simple. From this simple analysis, however, the criticality of certain parameters can be identified, and an understanding of the physics of the problem can be gained.

C.2.1 Occupant Kinematics in AAMA Crash Pulse Sequence. It is assumed, as stated by the industry, that the AAMA vehicle crash pulse (17.2 g peak, 125 ms half-sine deceleration) is indicative of a large number of frontal crashes. The crash pulse is shown in Figure C-1. This pulse is designed for sled testing of safety systems with no relative displacement, or crushing, of any vehicle structures. It is also assumed that the occupant compartment, and specifically the instrument panel (IP) will be decelerated according to this pulse. The position of the IP is of particular interest as this is the point at (or near) which the passenger-side air bag is anchored. In the case of the driver, the deceleration of the steering column is of interest, as this is where the driver-side air bag is attached. The IP will be the reference in the following analysis, but the steering column could be substituted just as easily. This is an important point in that recent statistics (Traffic Safety Facts 1995) show that the numbers for driver fatalities and injuries are roughly twice as large as those for passengers. Consideration of driver kinematics, therefore, is probably more important. It is assumed that the occupant is unbelted or “unrestrained.”

Both the occupant and IP are assumed to be traveling at 48 km/h (30 mph) at the start of the crash (at time $t=0$). For reference, 48 km/h (30 mph) is the integrated ΔV contained in the AAMA pulse. This pulse will decelerate the vehicle to zero velocity in 125 ms.

During the crash, the occupant (i.e., its center of mass) continues forward at 48 km/h (30 mph) while the IP is decelerated. This leads to a relative velocity and displacement of the occupant with respect to the IP. In this simple analysis, the occupant is treated as a simple point mass, neglecting obvious details related to the motion of specific body parts (e.g., head, legs, etc.) around the center of mass. The point of interest on the occupant can be defined as a point which is translated from the center of mass to a more relevant location (e.g., the surface of the chest). In this case, the kinematic calculations simply chart the motion of the chest surface with respect to the IP. Figure C-2 shows

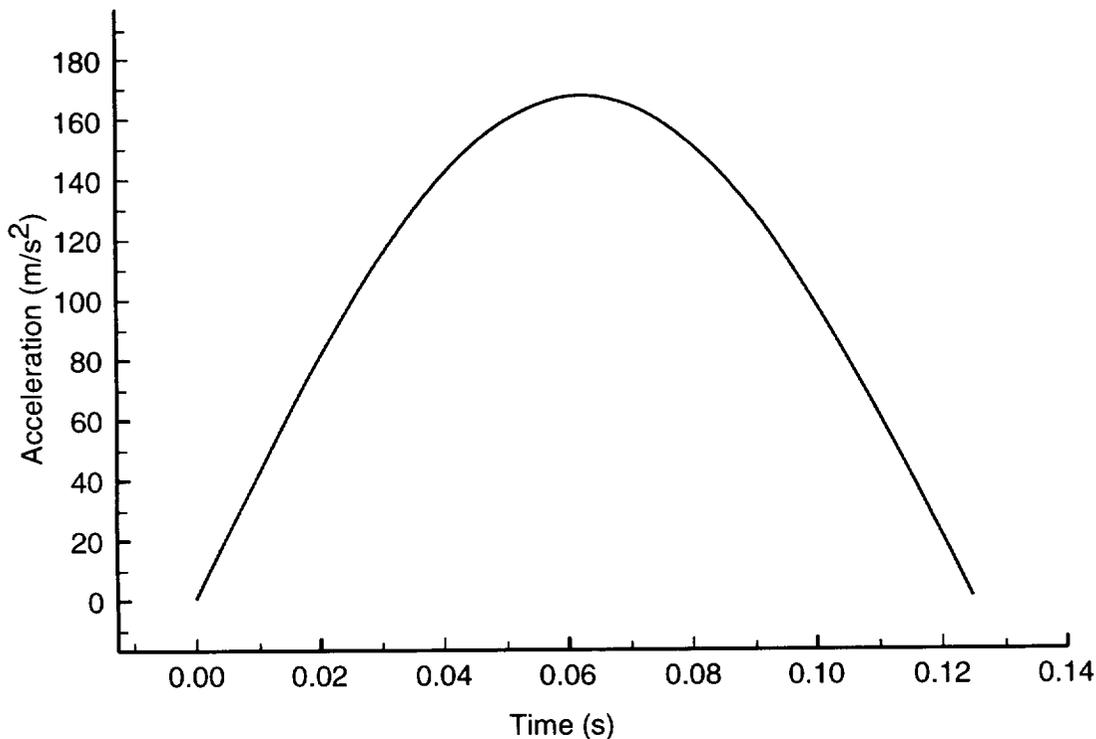


Figure C-1. AAMA Sled Pulse (17.1 g, 125 ms)

the closing velocity of the occupant with respect to the IP vs. time. Figure C-3 shows the relative displacement of the occupant with initial separations of both 30 cm (12 in.) and 60 cm (24 in.) from the IP, vs. time.

C.2.2 Application of Proximity Sensing to the Unrestrained-Occupant Scenario. It is assumed that the air bag deployment time will be determined with a crash sensor placed somewhere in the vehicle. For the generic sled test (with no structural deformation), the air bag deployment time has been fixed to 20 ms after the sled reaches an acceleration of 0.5 g. For the AAMA pulse, the air bag deployment time is approximately 21.2 ms. This is a relatively short time, only slightly longer than deployment times for more severe crashes [e.g., 48-km/h (30-mph), rigid frontal barrier crash] according to data that we have received.

Because 21.2 ms is a shorter discrimination time than may be found in some crashes, it is important to consider longer discrimination times (up to 40 ms). The analysis then concentrates on a range of discrimination times between 21.2 and 40 ms. Figure C-4 shows the velocity of the IP vs. time for the AAMA crash pulse. The early and late decision times are noted on this graph, along with the times corresponding to full bag deployment. The vehicle velocity change for each of the discrimination times is listed. For a 21.2 ms time, the vehicle has only slowed by 3.4 km/h (2.1 mph). Using this range of deployment decision times, the unbelted occupant position relative to the IP can be calculated at both the decision time and the time of full bag deployment. It is assumed that the bag is significantly filled at 30 ms after the deployment decision. By significantly filled, it is assumed that it has been inflated enough to fill a volume extending 15 cm (6 in.) from the IP. The 15 cm distance is not meant to reflect the performance of any real world air bag system. It is chosen

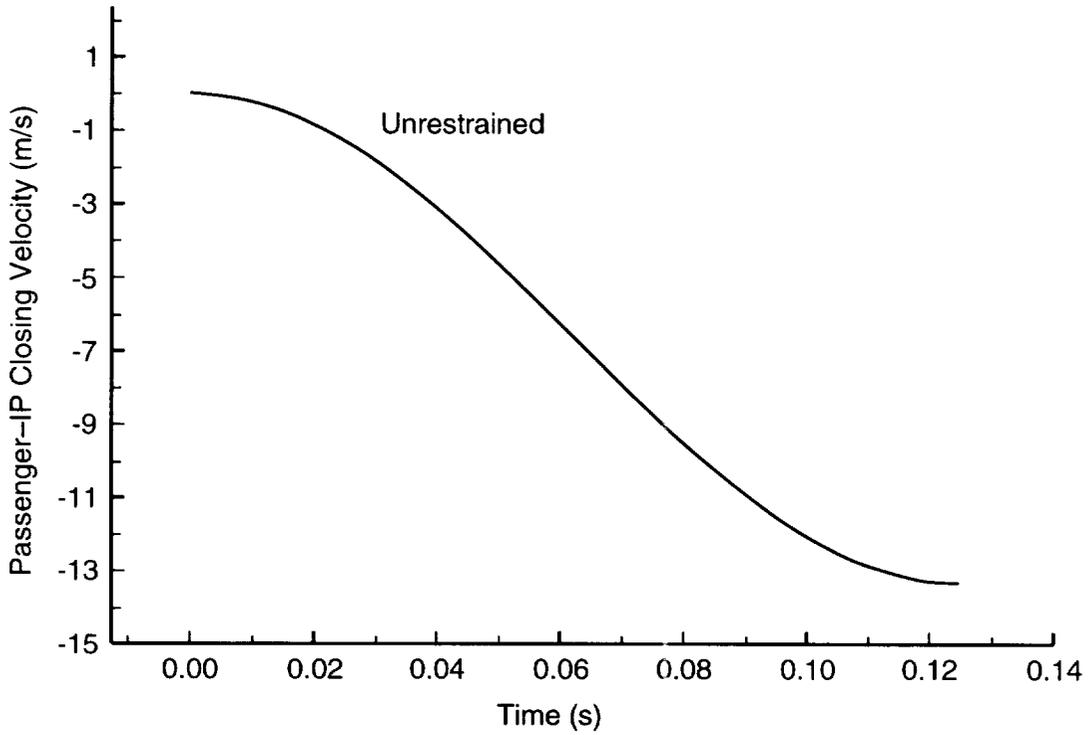


Figure C-2. Passenger-to-IP Closing Velocity at Entry to Keep-Out Zone for a 48-km/h (30-mph) Crash Versus Time

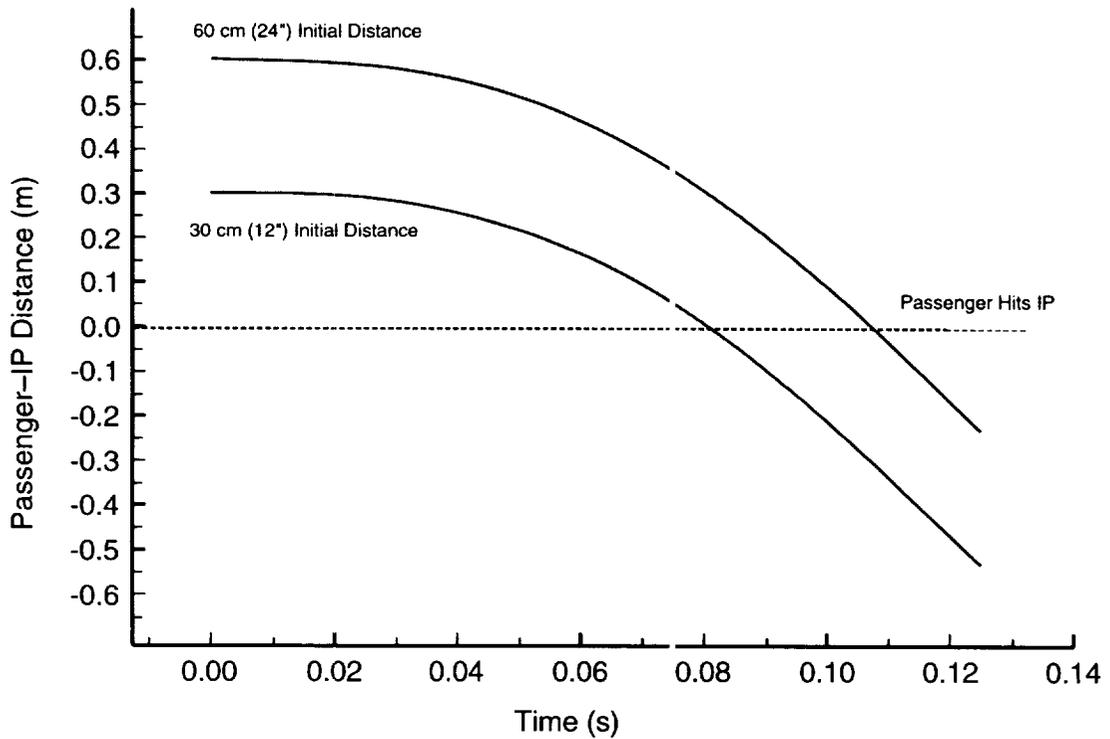


Figure C-3. Unrestrained-Passenger-to-IP Distance for a 48 km/h (30-mph) Crash Versus Time

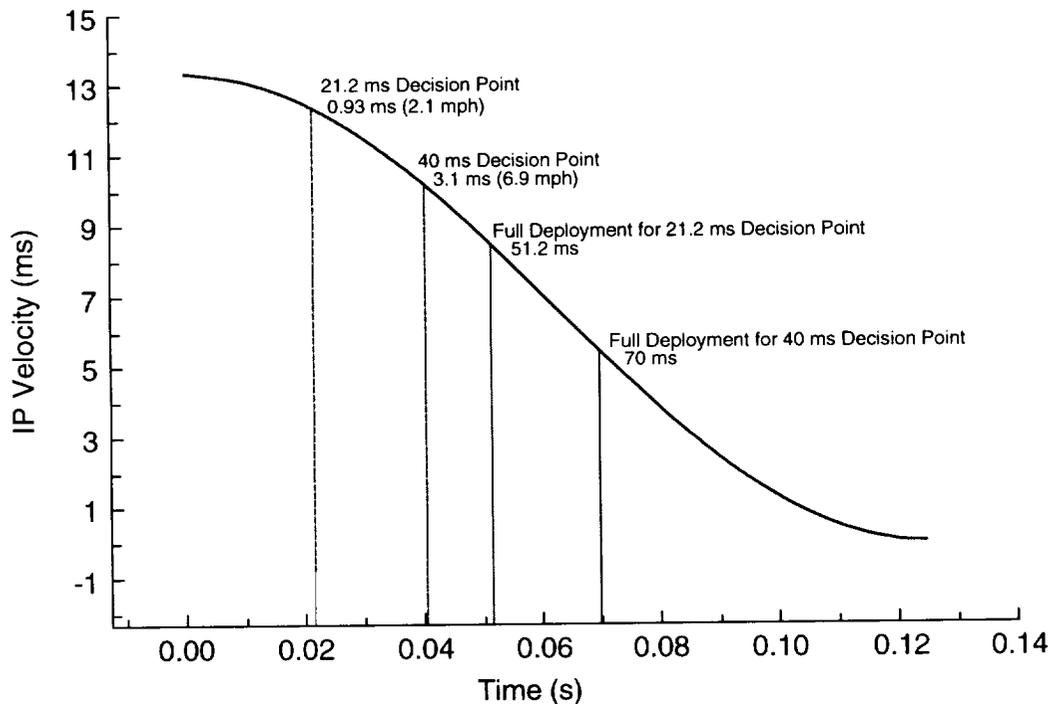


Figure C-4. IP Velocity at 21.2 ms and 40 ms (Late) Decision Times for the AAMA Crash Pulse; Full Deployment Times Assume 30-ms Bag Fill Time

only for the purposes of this discussion. Although the bag is not fully deployed at this time, the 15 cm (6 in.) distance is chosen as the edge of the keep-out zone, reflecting the observation that occupants interacting with a deploying air bag within this zone are at risk of inflation-induced injury (I^3). This assumption is consistent with the general understanding of the I^3 phenomenon presently held by the industry. In truth, the generic 30 ms time attributed to the bag deployment process is smaller when the bag's leading edge is only 15 cm from the IP. As will be apparent in the simulation data shown below, a small reduction in fill time will not greatly affect the conclusions that can be made. Using these assumptions, it is required in this study that the unrestrained occupant not enter this zone during (or before) the end of the 30-ms inflation time.

C.2.3 Analysis of Simple Keep-Out Zone. Figure C-5 shows the relative position of an occupant with respect to the IP for three initial distances 24 cm (9.3 in.), 36 cm (14.1 in.), and 60 cm (24 in.). A number of points can be made.

Figure C-5 reflects the current air bag situation (crash sensor determination of deployment time, with no proximity sensor). Two rectangles span the range of times, respectively, for deployment decision and corresponding "bag full," for deployment times between 21.2 and 40 ms. With an early deployment, most occupants all starting farther than 24 cm (9.3 in.) from the IP would remain outside of the keep-out zone during deployment. This is the intended early deployment scenario to protect unbelted occupants. Some number of occupants might be temporarily out of position (e.g., leaning forward) at a distance inside of 24 cm from the IP. It is well understood that these OOP cases could lead to harm.

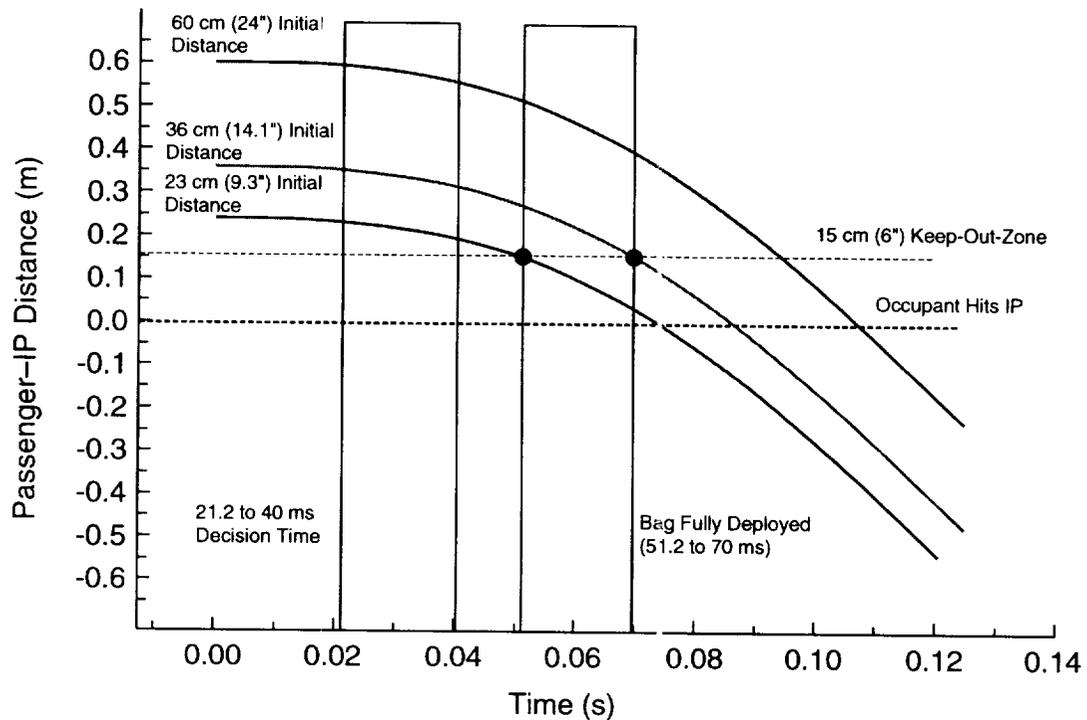


Figure C-5. Unrestrained-Passenger-to-IP Distance for a 48-km/h (30-mph) Crash Versus Time

For later deployments (e.g., 40 ms decision time) larger initial separations are required to remain outside of the 15 cm (6 in.) zone during deployment. An initial distance greater than 36 cm (14.1 in.) is required. This is fairly large, especially for drivers relative to the steering column. Based upon known seating positions, a significant total number of small drivers would be at serious risk in these late deployment events.

Most small drivers and all occupants with initial separations greater than 19 cm (7.6 in.) would be outside of the keep-out zone at the latest deployment decision time. For the early decision time (21.2 ms), all occupants outside of 16 cm (6.2 in.) would be outside of the 15 cm Keep-out zone at the deployment decision time. In these cases, a deployment decision based upon the occupant position relative to the 15 cm (6 in.) zone at the decision time would cause the air bag to be deployed, even though the motion of close-seated occupants, during the bag fill time, would cause them to enter the keep-out zone prior to full bag deployment and be subject to injury.

This analysis indicates that a simple deployment decision based upon a 15 cm (6 in.) zone would not prevent occupants from being in the zone during deployment, making them susceptible to IP. Later deployment clearly increases the problem. Assuming that a significant number of occupants fall within these ranges under “normal” conditions it is concluded that these occupants are both at risk with the present systems that have no proximity sensors, and would not be helped significantly with a proximity sensor, using a simple 15 cm (6 in.) keep-out zone.

C.2.4 Analysis of Separate Decision Zone. One possible solution worth considering is to define a separate, second keep-out zone that relates to the occupant’s *position at the deployment decision*

time. This new zone (“decision zone”) would necessarily be behind the 15 cm (6 in.) danger zone and closer to the occupant’s initial position. The position of the zone boundary can be chosen so that the forward trajectory of the occupant after the deployment decision carries him or her just to the edge of the true danger zone [15 cm (6 in.) assumed keep-out zone] at the bag-full time. This new zone would function in the same manner as the single keep-out zone described above:

- If inside the decision zone, then *suppress* or fire a lower-level bag.
- If outside the decision zone, then *deploy*.

The position of the decision zone boundary depends upon the deployment threshold. Figures C-6 and C-7 show both the trajectory and the zonal boundary positions for an unrestrained occupant during the typical 48 km/h (30 mph), AAMA crash pulse for 21.2 ms and 40 ms discrimination times, respectively. The graphs show the required initial separation of the occupant center of mass from the IP, in order to be just at the edge of the 15 cm (6 in.) zone at full deployment time. As stated above, the required separations are large, particularly for temporarily OOP situations. An important point is that the position of the decision zone boundaries [23 cm (9.1 in.) and 31.5 cm (12.4 in.), respectively] is very close to the assumed initial position of the occupant. In the case of an early deployment threshold, the difference between the initial position and the decision zone boundary is so small (0.2 in.) that the air bag will be (and should be!) shut off and on continuously, even with only very minor (as is typical) occupant motions.

To summarize: constructing an appropriate decision zone will in theory solve the major problem associated with a single 15 cm (6 in.) keep-out zone — occupant penetration during the time of bag deployment. However, the required position for the decision zone boundary and the required initial position of the occupant are significantly farther back than the 15 cm (6 in.) keep-out zone boundary. A large number of occupants (small-stature drivers, particularly) will be in a position to deactivate the bag. Based upon the earlier analysis, it is reiterated that the bag *should* be deactivated in these cases, as these unrestrained occupants would enter the danger zone and be harmed by the deploying air bag.

One concept for reducing the frequency of low-speed I³ episodes is to increase the deployment thresholds (effectively to higher velocity). The kinematic analysis shows, for a given initial position, the unrestrained occupants will be in greater danger as they will have had more time to move forward during the air bag deployment phase prior to full deployment. This is consistent with the concept discussed above (refer to Figure C-7). It is also consistent with the analysis of several groups that advocate never deploying an air bag past a certain time in the crash sequence. In contrast, the use of crash sensors/algorithms, to provide earlier deployment, would improve the dynamic performance of a proximity sensor.

In conclusion, proximity sensing with a single keep-out zone shutoff boundary is problematical if this boundary coincides with the edge of the danger zone in front of the air bag. Occupants that begin outside of the zone at deployment, may move into the zone during the 30-ms bag fill time.

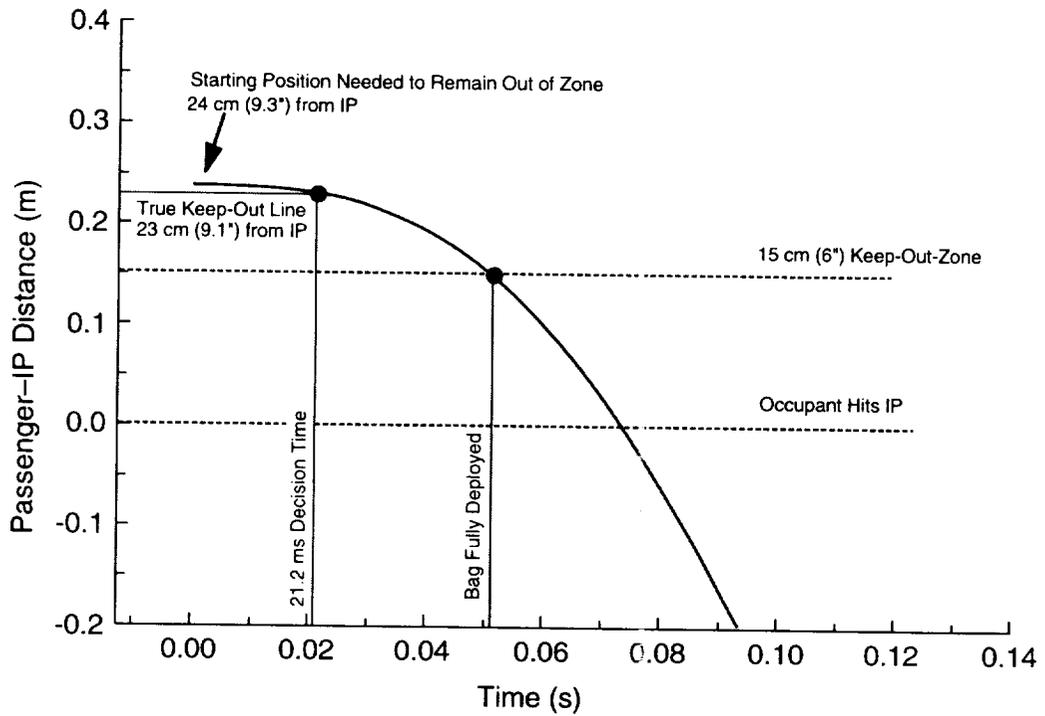


Figure C-6. Unrestrained-Passenger Trajectory for a 48-km/h (30-mph) Crash and 21.2 ms (Early) Deployment

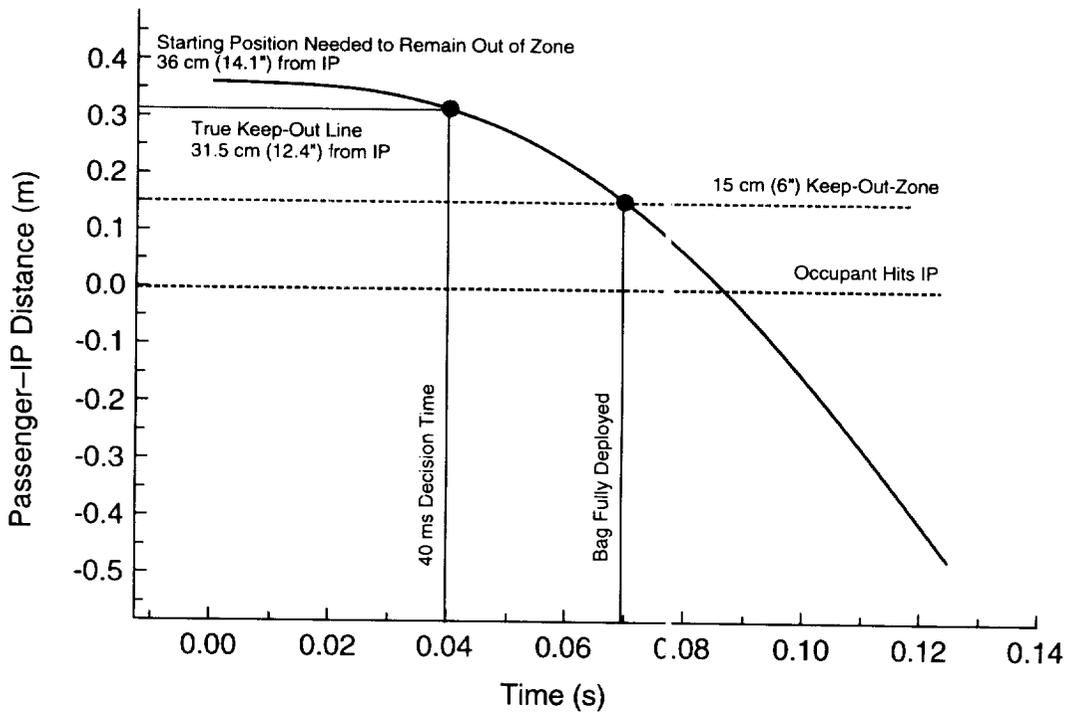


Figure C-7. Unrestrained-Passenger Trajectory for a 48-km/h (30-mph) Crash and 40 ms (Late) Deployment

Establishing a second, larger decision zone is one solution. The size of this decision zone depends strongly upon the crash discrimination time, and may be larger than the initial separation of many passengers from the IP (or steering column). Because of this, a proximity sensor-based system may ultimately suppress the air bag in a large number of cases. *A secondary conclusion from the kinematic analysis is that in current air bag-equipped vehicles (without proximity sensors), a large number of unrestrained occupants may be encountering deploying air bags in higher speed crashes. Those occupants closest to the IP are at the greatest risk.* Current air bag systems are likely to be causing injury in some of these cases. This, however, has not received the same public scrutiny as I³ episodes related to lower speed crashes. What remains to be understood (and is outside the scope of this analysis) is the marginal benefit of air bag deployment in these dynamic OOP situations. That is, is it better to encounter an expanding air bag in these dynamic OOP situations or to have no air bag at all?

These analyses are overly simplified. For example, a one-dimensional analysis of a keep-out zone neglects the fact that occupant kinematics and occupant-air bag interactions are really complicated three-dimensional problems in the real world. A detailed analysis would need to incorporate three-dimensional proximity sensing with a thorough understanding of the spatial dependence of a keep-out-zone for a real system. Similarly, the expected variability within a given system would have to be understood and accounted for in the analysis.

C.2.5 Dynamic Proximity Sensor Performance Requirements. Some of the issues associated with the use of dynamic proximity information have been conveyed above. Most of the problem appears to be unrelated to the proximity sensor itself. In addition to the effects of finite bag deployment time, there are also issues of variability in the performance of other system components (e.g., air bag inflators). Not only do these factors complicate analysis, but their effects may dominate the performance of the entire system including the proximity sensor. Putting these issues aside, some estimates for performance requirements related to proximity sensors can be derived. The focus is on four critical parameter specifications: resolution/accuracy, reliability, response time, and full-scale range. The focus on unbelted occupants is a major driver for some of these specifications. Specifically, it demands faster response times and larger full-scale ranges, as both the relative velocity and the free-flight distances are larger for the unrestrained occupant.

C.2.5.1 Resolution/Accuracy. Resolution/accuracy refers to the minimum detectable position change and the absolute error associated with the measurement of occupant position. For proximity sensors used in a keep-out algorithm, accurate detection of position relative to the IP (or steering wheel) will be crucial, as the keep-out zone is defined with respect to this reference point. The required accuracy (yet to be determined) should be specified as an absolute total system error, dx , defined as

$$dx = x_{\text{system output}} - x_{\text{actual}}$$

where $x_{\text{system output}}$ refers to the occupant position as measured by the proximity sensor system and x_{actual} is the true position of the occupant. Note that dx can be positive or negative. It is quite likely that some applications will be able to tolerate larger systemic errors that are of one sign (indicating

that the occupants, are closer than they really are, for example), than those of the opposite sign. It is important to note that resolution and accuracy may be strong functions of response time.

C.2.5.2 Reliability. See Section 4.3 and Appendix D for more information.

C.2.5.3 Speed/Response Time. Response time requirements for proximity sensors can be calculated only parametrically, at present. That is, if we assume a given error limit for proximity reported by the sensor, dx , then the required response time, t , is

$$t = dx / v_{occ}$$

where v_{occ} is the occupant velocity with respect to the proximity sensor.

A finite response time leads to an error related to the motion of the occupant during this time interval. If we state the maximum tolerable position error, then we can calculate a maximum tolerable response time for the sensor. It is important to note that the response time may be dominated by any one (or some or all) of a number of factors, including the following:

- inherent analog sensor response time
- digital sampling rate
- latency in digital computation system
- digital output rate to other systems.

Therefore, the inherent response time of the analog sensor at the front-end of the proximity sensor signal chain may or may not dominate the overall response time. Also, discrete sampling theory tells us that for a critically sampled (i.e., nonaliased) analog sensor, contributions to the response times from digital sources (sampling/output rate, computer latency) are *indistinguishable* from those of the analog sensor. All sources may contribute, and all must be considered.

Refer to Figure C-2, which shows v_{occ} vs. time for the case of an unrestrained occupant experiencing a typical crash pulse. At the decision times for air bag deployment (21.2 ms to 40 ms for early to late deployment, as described above), the relative unrestrained occupant velocity ranges from 0.93 ms (93 cm/s) to 6.22 ms (310 cm/s). (It is just equal to the instantaneous change in velocity of the IP.) The required response time for a proximity sensor, therefore, ranges from 10.7 ms to 3.2 ms per cm of allowed error. Once again, the required measurement accuracy is somewhat unknown at present. It involves details of the occupant/air bag interaction and a thorough examination of injury criteria. In many dynamic cases, these numbers indicate that fast response will be important. Because of this, it is important to note that the relationship between response time and position error may dominate the sensor's inherent resolution/accuracy in a dynamic measurement.

C.2.5.4 Full-Scale Range. This specification refers to the need for the proximity sensor to have a large enough measurement range. It must be able to sense occupant motion at some maximum distance, in order to measure occupant penetration into a decision zone. As stated above, the decision zone must be larger than 31.5 cm (12.4 in.) for an unrestrained occupant with a late deployment

threshold in a standard AAMA crash scenario. The ability to sense the occupant at even larger distances (i.e., those corresponding to the initial position of a large adult) would be important.

C.3 QUASI-STATIC PROXIMITY SENSING

This analysis turns from the potential difficulties associated with the use of dynamic proximity information, to the specific application of static proximity sensing. Here, the intention is to disable (or modulate) air bag inflation in response to a quasistatic OOP situation. By quasistatic, reference is made to a situation in which the OOP occupant is in a danger zone for a relatively large amount of time prior to the beginning of the crash. This larger residence time distinguishes the quasistatic situation from the dynamic scenario above. The same evaluation criteria can be used as with the dynamic problem. That is, proximity sensor system specifications for resolution/accuracy, reliability, response time, and full-scale range are also important in this application. The requirements for the first two (resolution/accuracy and reliability) in the quasistatic application are similar to those for the dynamic one. The one potential benefit of longer integration times is the reduction of random noise in the system. This can improve both resolution and accuracy.

The requirements for the sensor system response time and the full-scale range are modified significantly. Regarding response time, it can be assumed that based upon the conclusions regarding dynamic proximity sensing, the sensor should not shut off the air bag for an initially in-position, unrestrained occupant. Clearly, this is an arguable assumption. In other words, the proximity sensor should have no effect on the dynamic performance of the current air bag system. The static proximity sensor is to be used only to modulate air bag deployment for an occupant who has a large residence time in an initially defined danger zone. In order to achieve this, the sensor must not respond too quickly. Specifically, the response time, t , must be larger than the time interval between the start of the crash and the deployment decision time (21 to 40 ms for the AAMA pulse). Faster response times would allow the air bag to be shut off in some dynamic scenarios involving initially in-position occupants. This should be avoided. In some situations, it is desirable that there be a maximum response time. That is, the quasi-static detection system should be able to detect slow motion of an occupant into or out of the danger zone prior to the beginning of the crash. The alternative, namely determining occupant position only at vehicle start-up, for instance, would not be as useful. These two requirements (no dynamic air bag modulation and ability to detect slow motion of an occupant), therefore, bound the response time

$$t_{\min} < t < t_{\max}$$

where

$t_{\min} \sim 21$ to 40 ms, determined by the desire NOT to affect dynamic performance

and

t_{\max} is chosen low enough to detect occupant-initiated motion into and out of a danger zone. Estimates for t_{\max} in the range of 0.2 to 2 s seem appropriate.

The full-scale range for a quasi-static proximity sensor can be smaller than used for dynamic sensing, as the intent is to measure only occupant intrusion into a smaller danger zone (nominally 15 cm, as stated above). Sensor systems placed in or near the instrument panel would have smaller range requirements in the quasi-static applications. For sensors mounted in the seat back or certain positions of the headliner (as has been proposed by some groups), the range requirements may not be significantly reduced, as the sensor location may be far from the zonal boundary.

APPENDIX D—AIR BAG DEPLOYMENT RELIABILITY

Appendix D—Air Bag Deployment Reliability

Air bag subsystem mechanical reliabilities are critical parameters that need to be investigated. It is also important to consider the functional reliability of the air bag system since air bag failures, either failure to deploy or inappropriate deployment, could lead to serious injuries. The following analysis is a preliminary investigation of subsystem mechanical reliability requirements and how such requirements in conjunction with changes in air bag technology affect the functional reliability of the air bag system.

$$N_1 = \text{intended deployments}$$

$$N_2 = \text{unintended deployments}$$

$$N_3 = \text{unintended nondeployments}$$

$$N_o = N_1 + N_2 = \text{observed number of deployments}$$

$$N_1 = \lambda N_o,$$

$$N_2 = (1 - \lambda) N_o$$

where λ is the fraction of intended deployments with respect to the total deployments.

System Deployment Functional Reliability is given by

$$\begin{aligned} \frac{N_1}{N_1 + N_2 + N_3} &= 1 - \frac{N_2 + N_3}{N_1 + N_2 + N_3} \\ &= 1 - \frac{(1 - \lambda)N_o + N_3}{N_o + N_3} \end{aligned}$$

But the convolution of subsystem mechanical reliabilities measures

$$\begin{aligned} \frac{N_1}{N_1 + N_3} &= 1 - \frac{N_3}{N_1 + N_3} \\ &= 1 - \frac{N_3}{\lambda N_o + N_3} \end{aligned}$$

Only when there are no unintended deployments (i.e., $\lambda = 1$) are these the same. Subsystem performance or a deployment decision algorithm that allows an arbitrary number of unintended deployments will always permit meeting a goal of minimal unintended nondeployments.

If it is assumed that air bag deployment subsystems are engineered to meet performance standards under the most severe environmental and crash severity conditions, then it is reasonable to assume statistical independence when convolving subsystem mechanical reliability into system mechanical reliability. Suppose there are four subsystems (e.g., crash sensor, control system, inflator, and air bag) with mechanical performance reliabilities $1-\alpha_i$; $i = 1, \dots, 4$. Then, system mechanical reliability is given by

$$\prod_{i=1}^4 (1-\alpha_i)$$

A subsystem mechanical reliability requirement can be defined in terms of an average subsystem mechanical reliability, $1-\alpha$, where

$$(1-\alpha)^4 = \prod_{i=1}^4 (1-\alpha_i)$$

For 1994 $N_o = 62 \times 10^3$, and there were about 23×10^6 driver-side air bags and 5×10^6 passenger-side air bags. Assuming the driver/passenger air bag deployment ratio is the same as the driver/passenger installed air bag ratio the convolution of subsystem mechanical performance reliability for driver-side air bags is given by

$$R_{MD} = 1 - \frac{N_3}{\lambda(23/28)(62 \times 10^3) + N_3} = (1-\alpha)^4$$

The analogous System Deployment Functional Reliability, R_{FD} , the probability of an intended deployment, is given by

$$R_{FD} = 1 - \frac{(1-\lambda)(23/28)(62 \times 10^3) + N_3}{(23/28)(62 \times 10^3) + N_3}$$

The trade-off between minimizing the number of unintended nondeployments and increasing the number of unintended deployments is illustrated in the following two tables.

$N_3 = 1$	λ	α	R_{MD}	R_{FD}
	0.5	9.8×10^{-6}	0.99996	0.49999
	0.9	5.5×10^{-6}	0.99998	0.89998
	0.99	5.0×10^{-6}	0.99998	0.98998
	1.0	4.9×10^{-6}	0.99998	0.99998
$N_3 = 10$	λ	α	R_{MD}	R_{FD}
	0.5	9.8×10^{-5}	0.99961	0.49990
	0.9	5.45×10^{-5}	0.99978	0.89982
	0.99	5.0×10^{-5}	0.99980	0.98981
	1.0	4.9×10^{-5}	0.99980	0.99980

If N_3 is specified as an absolute standard then the growth in air bag installments will lead to increased subsystem mechanical reliability requirements. If, however, N_3 is specified as a small fraction of observed deployments then, if deployments are approximately proportional to installments, the mechanical reliability requirements will be unchanged.

For fixed subsystem mechanical reliabilities it is also possible to consider how changes in the number of deployments affect the number of unintended nondeployments as a function of the fraction of unintended deployments. Let r be the fraction of driver side deployments.

$$1 - \frac{N_3}{\lambda r N_o + N_3} = \prod_{i=1}^4 (1 - \alpha_i)$$

$$N_3 = \frac{\left[1 - \prod_{i=1}^4 (1 - \alpha_i) \right] \lambda r N_o}{\prod_{i=1}^4 (1 - \alpha_i)}$$

Future work should assess the relevance of the reliability requirements in terms of current and future air bag systems. If future systems add capability, they will become more complex, and subsystem mechanical reliability requirements will increase. The implications of this should be explored.

APPENDIX E—HUMAN INJURY RISK CRITERIA

APPENDIX E—HUMAN INJURY RISK CRITERIA

E.1 BACKGROUND

Biomechanical data collected in the past provide the distributions of injury risk to occupants in vehicle collisions. This information is vital to the development of criteria for evaluating automotive restraint systems. In 1984, General Motors Corporation published a set of Injury Assessment Reference Values (IARVs) [1] for assessing injury severity associated with the various biomechanical response measurements of the Hybrid III, 50th-percentile adult male dummy. Qualitatively, IARVs were to refer “to a human response level, below which a specified significant injury is considered unlikely to occur for an individual.” Development of the risk curves is an evolutionary process with a foundation in earlier efforts to define risk boundaries, i.e., IARVs. IARVs have been supplemented by the injury risk curves shown in Figures E-1 through E-9. These curves were developed by Mertz [14] to express risk of human injury as a function of Hybrid III dummy response.

The Hybrid III 50th-percentile male dummy was developed by General Motors [1,13] to address the biofidelity and measurement deficiencies of the Hybrid II dummy. This dummy was designed to approximate the size, shape, and mass of the 50th-percentile adult male. The dummy’s skeleton is composed primarily of metal parts; a vinyl skin and foam covers the structure to give the desired external human shape. The Hybrid III responses mimic human responses in head acceleration for forehead and side-of-the-head impacts, neck flexion and extension, and chest force-deflection for blunt and distributed sternal impacts; Hybrid III knee response can be calibrated with respect to human knee impact response.

In 1987, Ohio State University(OSU) initiated development of a multisized Hybrid III-based dummy family. Based on the anthropometry of the U.S. adult population, body-segment lengths and weights were selected for an adult-size large male (Hybrid III 95th-percentile Male) dummy and an adult-size small female (Hybrid III 5th-percentile Female) dummy. The various child and infant dummies were developed by GM, an SAE task force, and OSU to identify the injury potential associated with the interaction of the deploying cushion and child and rearward facing infants. Summaries of the standard instrumentation for the Hybrid III dummies are given by Mertz [19].

Human injury is usually characterized according to the Abbreviated Injury Scale shown in Table E-1 [24]. In the AIS system, injury is classified by severity on a numerical scale from one to six. A description of severity and probability of fatality are shown in Table E-1. Injury risk curves for head injury are presented in Figures E-1 and E-2, for thoracic injury in Figures E-3, E-4, E-5, and E-6, and for neck injury in Figures E-7, E-8, and E-9. All risk curves are based on normally distributed risk criteria, the justification being grounded in the approximate normality of human sizes and tissue strengths.

E.2 THORACIC INJURY RISK

The test criteria for assessing thoracic injury risk are chest compression, $V \cdot C$, and the rate of thoracic compression [24]. Chest compression (sternal deflection) of the Hybrid III dummies is the most meaningful parameter for injury assessment for blunt thoracic impact. Peak chest deflection

is measured in the midsagittal plane and indicates the change in distance between the sternum and spinal column. The compression deflection is measured by a central rotary potentiometer in the Hybrid III dummy.

Figure E-3 is a plot of the risk of AIS 3+ thoracic injury due to shoulder belt loading vs. Hybrid III midsize male sternal deflection. Figure E-4 is a plot of the risk of AIS 3+ and AIS 4+ thoracic injury due to distributed loading (air bag) vs. normalized sternal deflection. Figure E-5 is a plot of the risk of AIS 3+ thoracic injury vs. maximum rate of thoracic compression as measured on Hybrid III 3 yr., 6 yr., small female, midsize male, and large male dummies. Figure E-6 is a plot of AIS 4+ thoracic injury risk vs. the "viscous criterion," $V \cdot C$.

Lau and Viano [10] discuss the history of the use of various criteria for predicting thoracic injury: the acceleration criterion, the force criterion, and the compression criterion. That discussion describes the capabilities and limitations of various injury criteria in adequately predicting thoracic injury severity at a level threatening occupant survival, and they provide a foundation for the introduction of the viscous criterion.

The acceleration criterion is based on a measure of spinal acceleration. Since the human torso is not a rigid mass, such a measure cannot account for the causal role of body deformation in thorax injury experience. At best, such a criterion could predict the severity of skeletal injury. However, the empirical evidence available suggests that a model adequately explaining observation might look like Figure E-13. A, B, and C refer to risk curves corresponding to different impact conditions, so that a single parametric curve cannot adequately explain skeletal injury risk. A given spinal acceleration produces different risk levels depending on the impact condition or, equivalently, the same risk corresponds to different levels of spinal acceleration depending on the impact condition. Spinal acceleration is therefore considered to be an inferior indicator of life-threatening thoracic injury compared to the criteria given above.

In the following discussion some specific model specification and estimation issues will be addressed with respect to the thoracic injury risk curves, based on an acceleration criterion generated in [22].

With regard to model specification, there are three major issues: (1) restriction of the estimated model to a linear response surface in logit space, (2) the use of age as an explanatory variable, and (3) the appropriateness of a fixed parameter model. It is not possible to account for interaction effects without using a higher-order response surface. Even with a single explanatory variable, such as the use of HIC for head injury risk, the data may suggest a nonlinear response surface, such as was presented by NHTSA in [22] in their extension of the Prasad-Mertz curves for head injury risk. In [22] age is introduced as a linear explanatory variable in logit space. However, an examination of the data base used to estimate the parametric model reveals that to be an inappropriate specification and the resulting statistical significance of age as an explanatory variable to be an artifact of the disparity between the specification and the data used. From the specimen data base, for subjects under the age of 40, AIS = 0 regardless of the spinal acceleration value, and for subjects over 40 the AIS level is only weakly correlated with age. Evans, in [4], provides evidence that fatality risk from similar physical insults is correlated with both age and gender. So there might be some expectation that this would also be true when severe thoracic injury is under consideration. Unfortunately, the

data base used to estimate the risk curves in question does not support that expectation. A final model specification criticism relates to the previous observation that no single fixed-parameter injury model based on spinal acceleration can explain risk level independent of impact conditions.

With regard to model estimation issues, the two major interconnected concerns are as follows: (1) that the thoracic injury risk curves presented in [22] do not completely account for the possibility that the injury risk distribution for the population of specimens in the data base may not be the same as that of the population at risk and (2) that there is a logical flaw in the creation of the risk curves called “age-independent” curves. Given that the estimated risk curves depend on both spinal acceleration and age, translating the age distribution from the distribution for specimens to the distribution of the population at risk was carried out. However, it may still be the case that a bias remains due to increased injury susceptibility of specimens compared to the population at risk. To a first-order approximation, the creation of age-independent curves amounts to replacing the explanatory variable, age, in the logistic curves by the average age of the population at risk. The frequency distribution of age in frontal impacts from NASS data yields an average age of approximately 32.7. Thus the age-independent curves approximately correspond to fixing age in the estimated logistic curves at a level within a range where the specimen data does not support the hypothesized age effect.

It may well be that injury risk *should* be dependent on age (and gender), and it is certainly desirable to adjust for differences in age (and gender) distributions between those of specimens and the population at risk. But that cannot be accomplished in a quantitatively meaningful way by ignoring the conflict between hypothesis and evidence.

The AIS 3 + chest injury risk curves developed by NHTSA and presented in [22], Tables II-6 and II-7, are reproduced in Figures E-14 and E-15. The risk curve labeled “Air Bag Restraints” was developed for unbelted occupants and the risk curve labeled “Belt Restraints” was developed for belted occupants. Our conclusion, as a result of the considerations described above, is that chest (spinal) acceleration has limited ability to predict chest injury and that the specific curves embed several technical flaws. Therefore, we consider that injury risk values derived from these curves for a given crash event have little credibility.

E.3 NECK INJURY RISK

The neck injury criteria are based on the measurements of flexion bending moment (Nm), extension bending moment (Nm), axial tension (N), axial compression, and fore/aft shear (N).

Figure E-7 is a plot of the risk of AIS 3+ neck injury vs. normalized neck tension, where normalization constants are provided for the Hybrid III 3 yr., 6 yr., small female, midsize male, and large male dummies, as well as the CRABI (Child Restraint Air-Bag Interaction) 6, 12, and 18 dummies. Figure E-8 is a plot of the risk of AIS 3+ neck injury vs. normalized extension moment. Again, normalization constants are provided for all the Hybrid III and CRABI dummies mentioned for Figure E-7. The risk of AIS 3+ neck injury vs. combined normalized neck tension and extension moment is shown in Figure E-9. Paired normalization constants are provided for all the Hybrid III and CRABI dummies mentioned for Figure E-8.

The JPL assessment utilizes neck injury risk curves. The neck injury risk curves developed by Mertz et al. [14], which are very recent, are the only comprehensive set of neck injury risk curves of which we are aware. There exist force-duration envelopes [1,13] constructed for the purpose of deriving neck protection reference values but those are not injury risk curves. The results of analysis using the neck injury risk curves should be consistent with the specifications derived for neck protection reference values from those force-duration envelopes.

E.4 HEAD INJURY CRITERION (HIC)

The Head Injury Criterion (HIC) has been used for over 20 years as a predictor of head injury risk in frontal impacts. References [18, 27 through 30] summarize the evolution of HIC, issues affecting its performance as a predictor, and the need to limit HIC duration.

Viano [27] describes the historical roots of HIC in tests involving direct head impact. In early application to unrestrained occupants, HIC duration was implicitly limited by the unbelted status of the occupants. As belt use increased, the lack of an explicit duration constraint became important since the belt use itself increased HIC by increasing duration, but decreased risk by reducing the chance of head impact. Both Viano [27] and Mertz et al. [18] provide support for limiting HIC duration to 15 ms in accordance with the implicit limit in the early tests used to justify real-world relevance for HIC as a measure of head injury risk.

A 15-ms HIC duration limit was also recommended in the NHTSA report [11], research supported by the NHTSA Office of Crashworthiness Research. Quoting from [11], “The best choice for a head trauma assessment criterion would appear to be the HIC method, but with a limit on the time interval over which it is calculated. This limit is important because the biomechanical basis for the HIC method is direct head impact. Thus, we recommend a value of $HIC = 1000$, for $(t_2 - t_1) \leq 15$ ms.”

The Federal Motor Vehicle Safety Standard 208 uses 36-ms HIC values. This results in overstating head injury risk for restrained occupants. The HIC criterion is defined by

$$HIC = \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a \, dt \right]^{2.5} \times (t_2 - t_1)$$

where a is a resultant head acceleration and $t_2 - t_1 \leq 15$ ms for 15-ms HIC. Figure E-1 is a plot of the risk of AIS 4+ Brain Injury vs. HIC for the adult population. Figure E-2 is a plot of the risk of Skull Fracture vs. Peak Head Acceleration for the adult population.

Skull fracture risk curves based on HIC have also been developed by Hertz [5]. Those curves are depicted in Figure E-12 together with the skull fracture risk curve of Mertz from [18]. Mertz et al. in [18] provided a succinct critique of the Hertz curves, illustrating their lack of real-world credibility. The following discussion repeats and expands on that.

The objective in developing head injury risk curves based on HIC is to find the threshold distribution of injury. However, all cadaver specimen data is necessarily censored so that only failure/nonfailure response to experienced HIC levels is available. The Hertz method was to assume three alternative

functional forms—normal, 2-parameter Weibull, and 2-parameter lognormal—and to estimate distributional parameters using the maximum likelihood method with an embedded algorithm which attempts to account for the effects of censoring. The ability of any censoring algorithm to correct for the effects of censoring is dependent on whether assumptions embedded in the algorithm match the censoring pattern of the data. The existence of a censoring algorithm does not guarantee that it will produce credible results for a given data set. If estimated curves fail sanity checks, that is indicative that the algorithm in question is not robust with respect to the censoring pattern of the data used. The Hertz method does not take into account that the threshold failure distribution of the specimens is not the same as that of the population at risk. As mentioned previously, the approximate normality of human sizes and tissue strengths provides a heuristic justification for the expectation that injury threshold distributions incorporate such knowledge into the specification of distributional functional form. It is unclear if any justification beyond ease of computation and conservatism for lower HIC values can be advanced to support the choice of 2-parameter Weibull or lognormal forms.

The Mertz/Weber estimation method is described compactly in [18]. This method has its foundation in a nonparametric estimation method for uncensored data. It accommodates the fact that all data is censored. The accuracy of this method (or any alternative) depends on correctly specifying distributional functional form and obtaining reasonable estimates for the failure threshold of the weakest and strongest specimens in the sample. In contrast with the Hertz method, the failure distribution of the specimens does not have to match the failure threshold distribution of the population at risk.

Referring to Figure E-12, the most direct comparison of the Hertz curves with that of Mertz is for the normal distribution. That is the only one of Hertz's curves which is not constrained to pass through zero. If the failure threshold distribution is approximately normal, the probability of values below $HIC = 0$ must be negligible. That is so for the estimated normal curve of Mertz, but the estimated normal curve of Hertz yields the noncredible result that the probability of skull fracture when $HIC = 0$ is 10%. That result shows that the estimation method's censoring algorithm does not produce sensible results for this data set. In particular, it overstates the underlying variance of the failure threshold distribution. That is obscured by fitting Weibull and lognormal forms with the curves constrained to pass through zero. However, for the data base in Reference [18] the seven lowest values of HIC experienced correspond to nonfailures. Mertz's curve yields the likelihood of such an occurrence as approximately 94%, whereas Hertz's normal and lognormal curves produce corresponding likelihoods of approximately 24% and 53%, lending support to the suspicion raised by the normal curve estimate, that the failure threshold probability is overstated for lower values of HIC in the Hertz curves. A procedure for examining the robustness of the censoring algorithm for Weibull or lognormal forms characterizing the failure threshold distribution using the specimen data base would be to estimate 3-parameter forms to see if the estimated location parameters are significantly different from zero.

Figure E-16 is a plot of the AIS ≥ 4 Head Injury Risk Curve developed by Mertz et al., reproduced from Figure E-1, the corresponding NHTSA lognormal risk curve, reconstructed from Table II-2 in [22], and the NHTSA lognormal fatality risk curve given in Table II-2 of [22]. Although the NHTSA lognormal risk curve for life-threatening head injury as a function of HIC lies below the Mertz

curve, the assessed risk in a given crash test may be higher based on the lognormal curve since NHTSA uses 36-ms HIC to assess risk while Mertz uses 15-ms HIC.

If HIC is to be used as an *unbiased* risk criterion for head injury, it is our conclusion that the Mertz head injury curves are the most appropriate of those available and that 15-ms HIC must be used to preserve the biomechanical rationale for the use of HIC.

E.5 APPLICATION OF INJURY RISK CURVES

As the development of injury risk curves evolves and additional experimental evidence is introduced, the estimation of the absolute level of risk associated with a risk criterion will change. However, in the use of these curves for the JPL injury assessment process to evaluate the effects of technological changes from a baseline, our measures will be the relative change in risk levels. Such measures will not be significantly affected by other than radical changes in the injury risk curves themselves.

Table E-1. Abbreviated Injury Scale (AIS) and Percent Fatality Associated with AIS Levels

AIS	Severity	Fatality Range (%)
1	Minor	0.0
2	Moderate	0.1–0.4
3	Serious	0.8–2.1
4	Severe	7.9–10.6
5	Critical	53.1–58.4
6	Maximum Injury (Virtually Unsurvivable)	>58

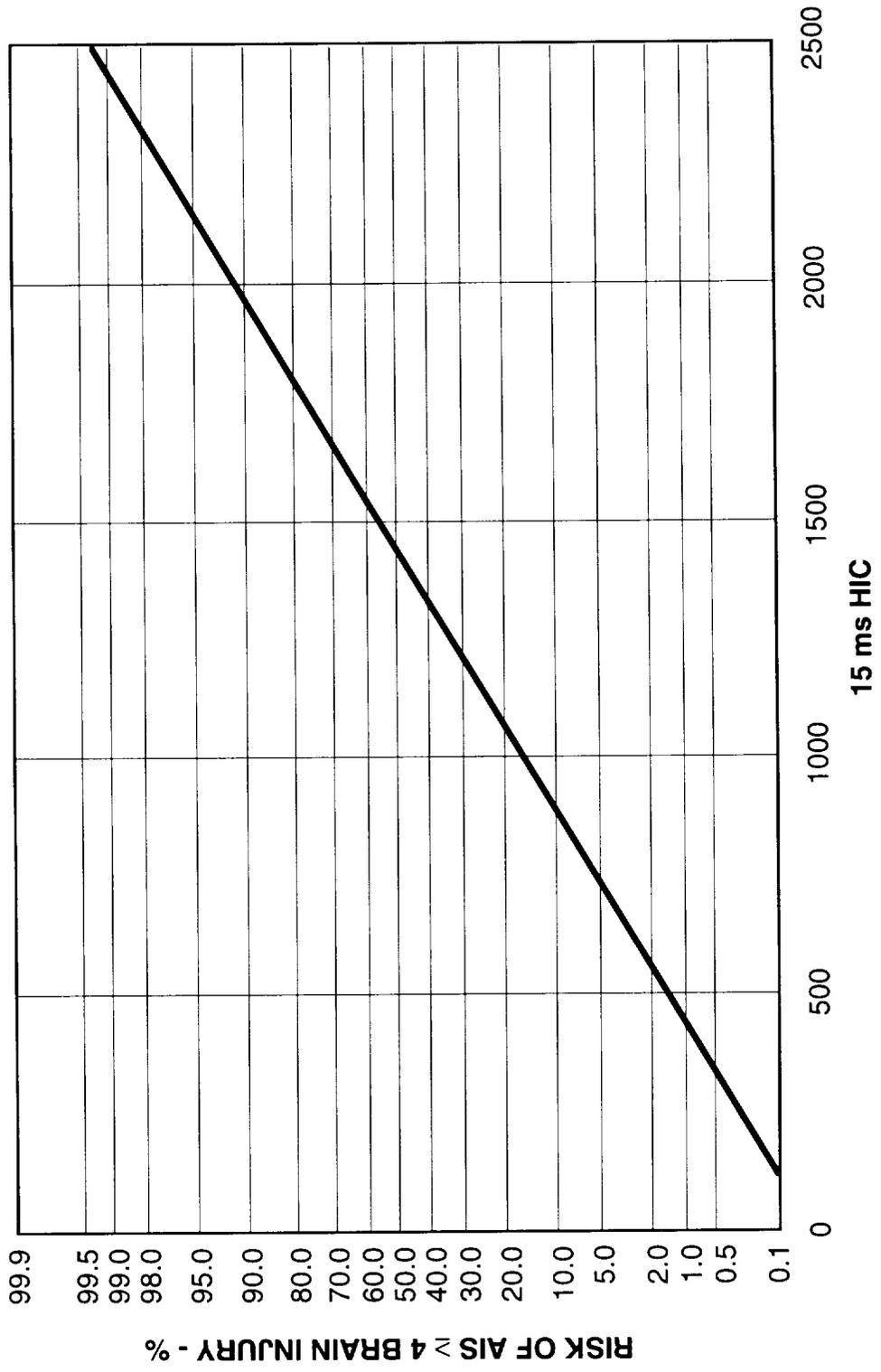


Figure E-1. Risk of AIS ≥ 4 Brain Injury as a Function of HIC for Adult Population

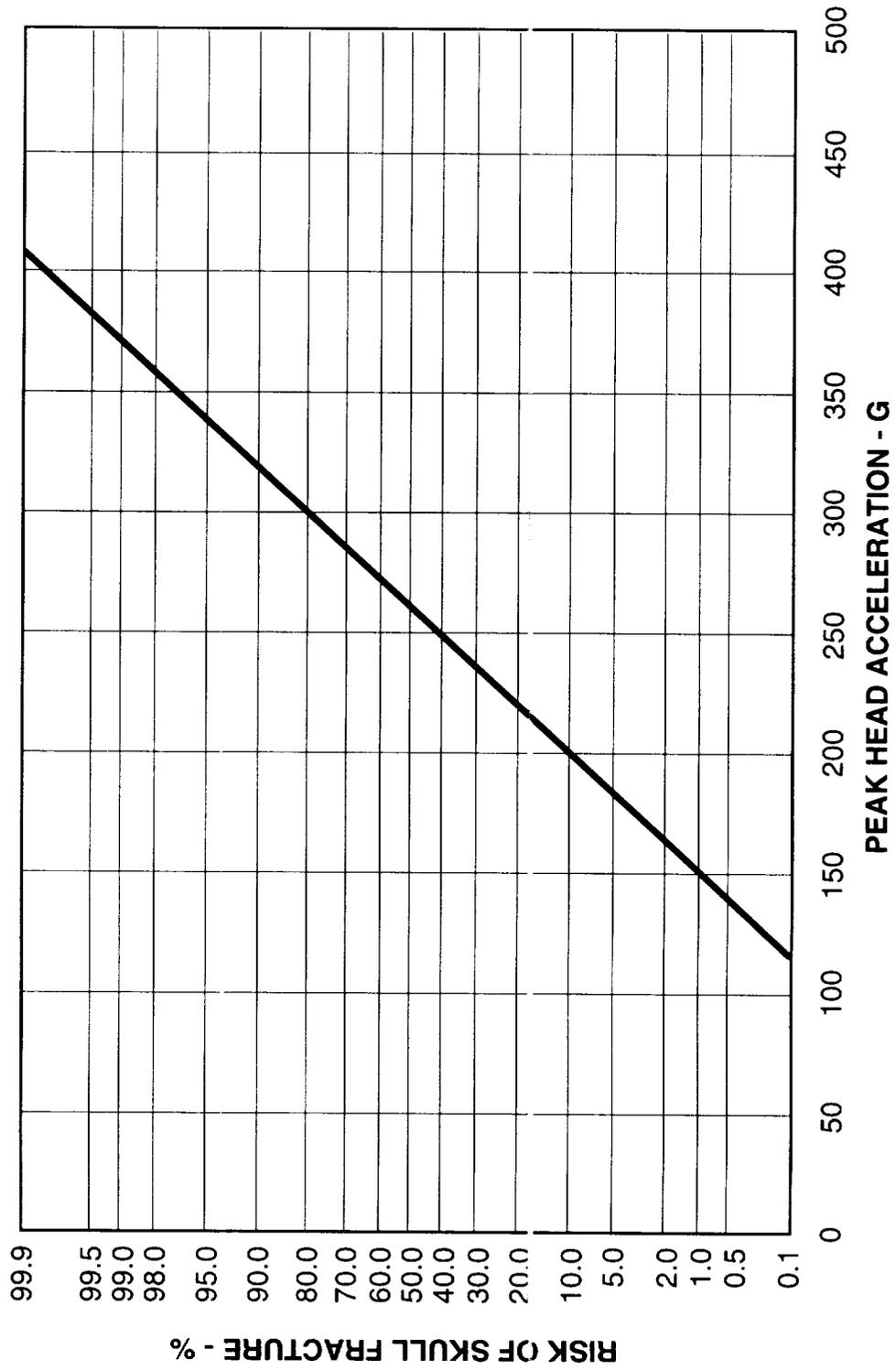


Figure E-2. Risk of Skull Fracture as a Function of Peak Head Acceleration for Adult Population

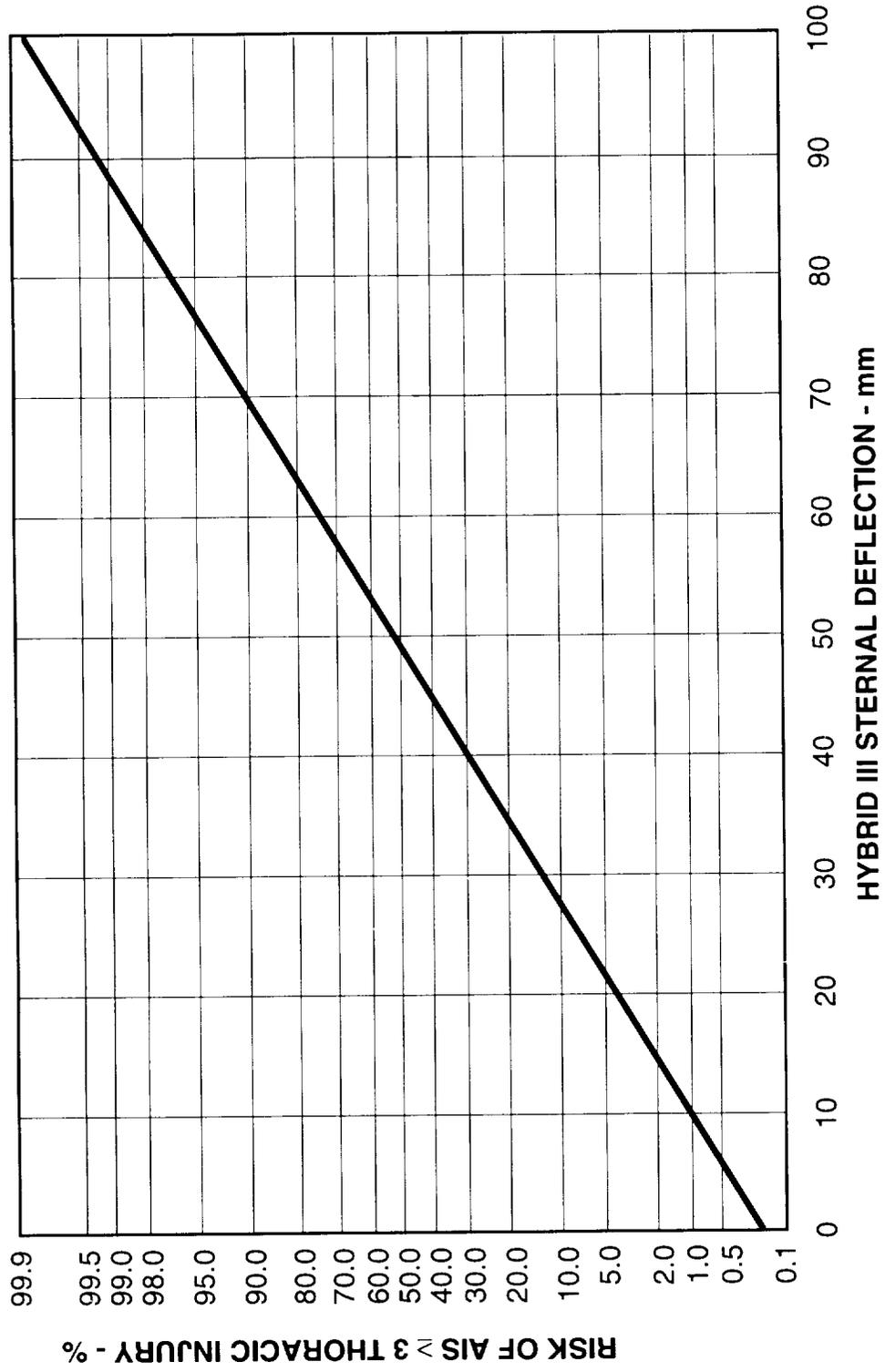


Figure E-3. Risk of AIS \geq 3 Thoracic Injury Due to Shoulder Belt Loading as a Function of Hybrid III Sternal Deflection

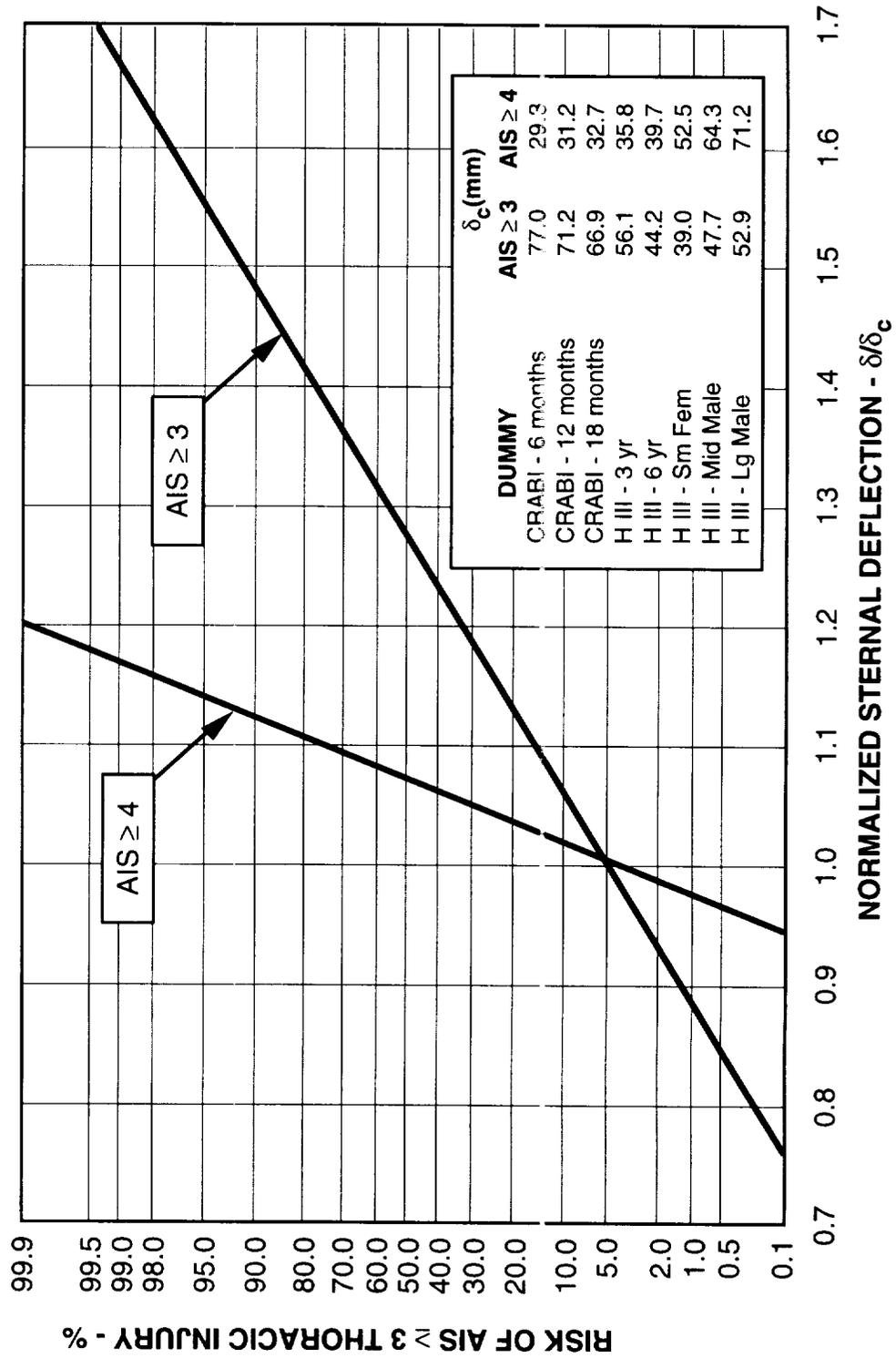


Figure E-4. Risk of AIS \geq 3 Rib Fractures and AIS \geq 4 Thoracic Organ Injury for Distributed Chest Impacts as a Function of Normalized Sternal Deflection

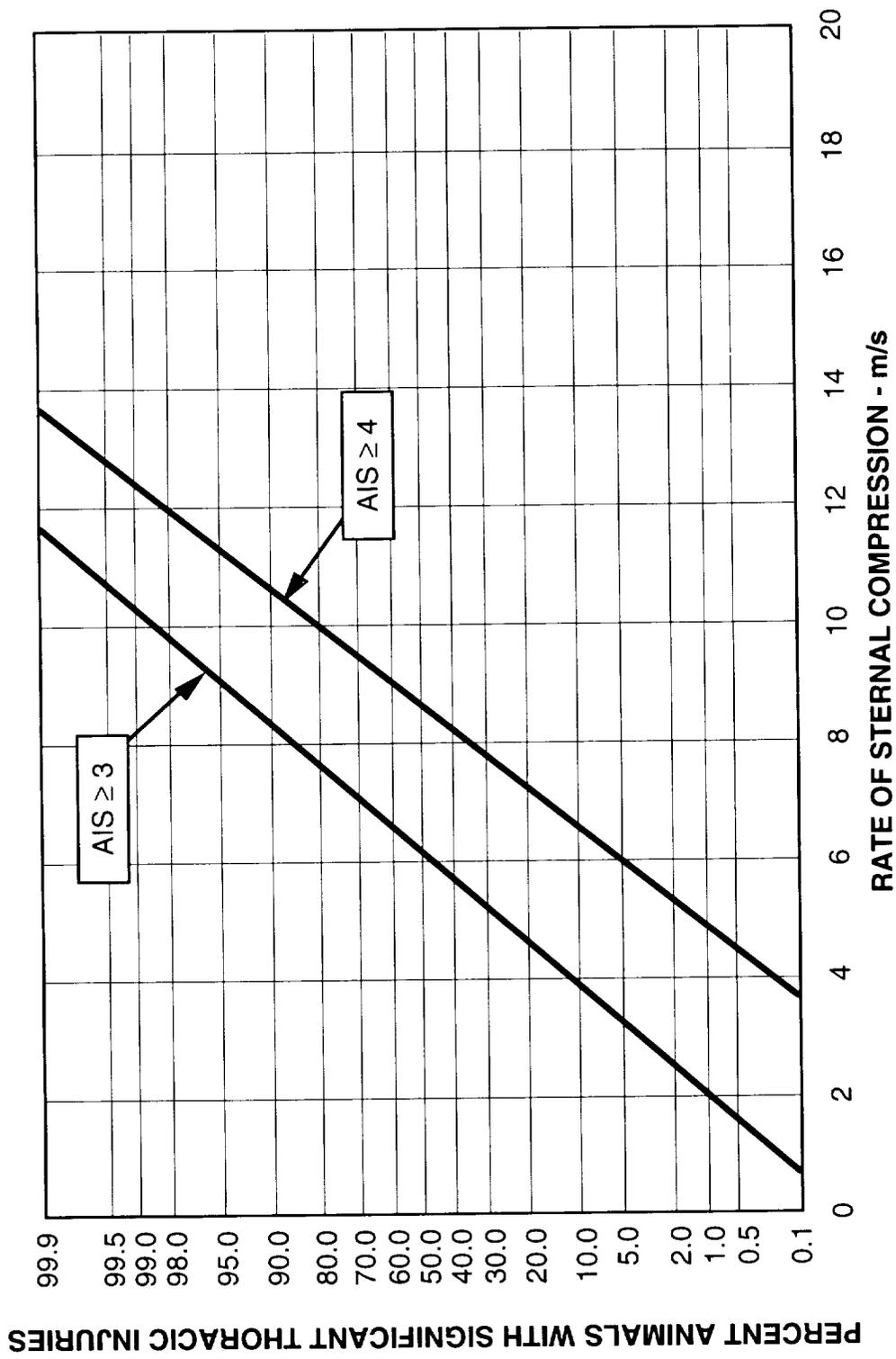


Figure E-5. Risk of AIS ≥ 3 and AIS ≥ 4 Heart/Lung Injury as Function of Rate of Sternal Deflection

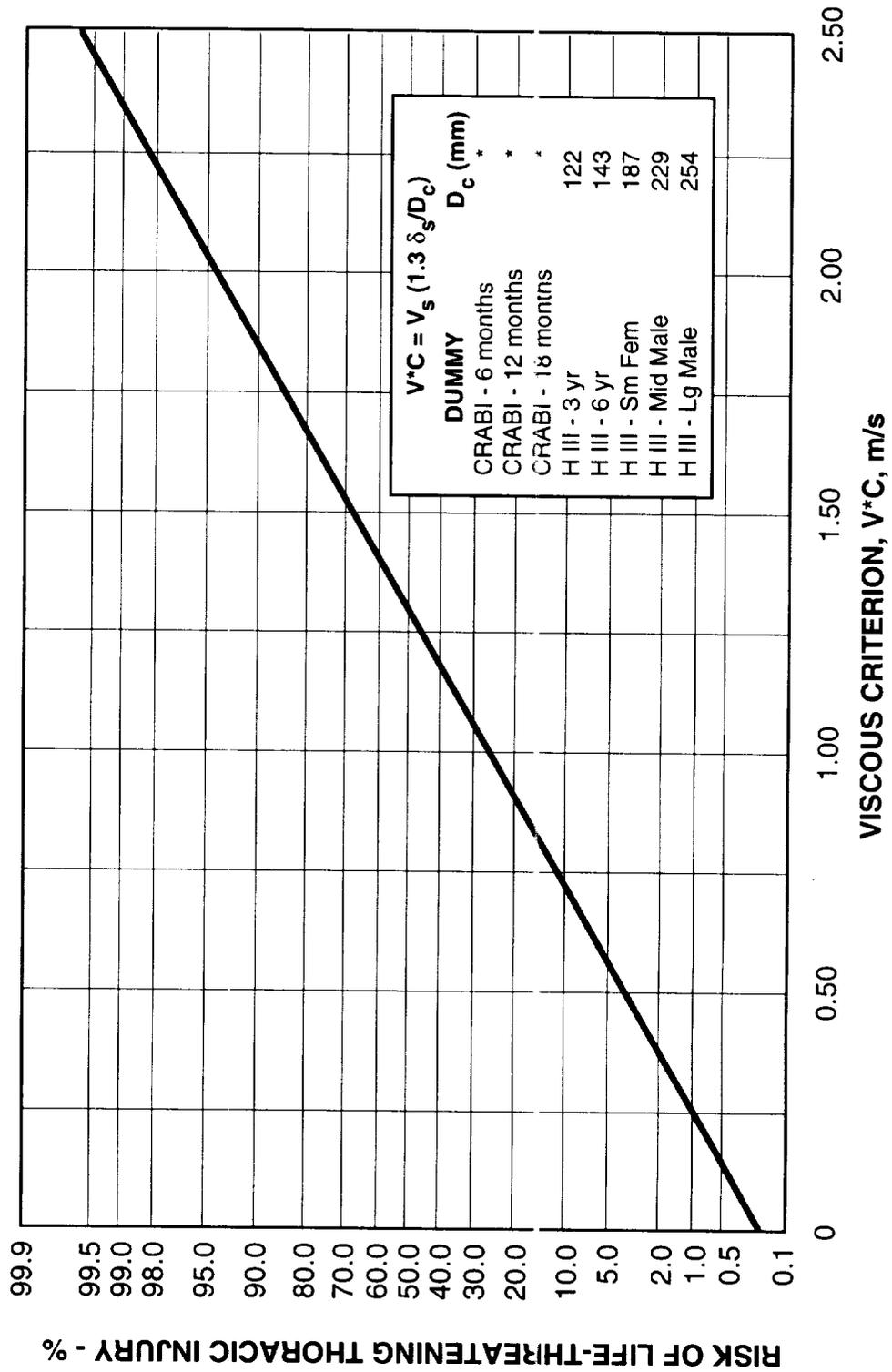


Figure E-6. Risk of AIS ≥ 4 Thoracic Injury as a Function of the Viscous Criterion, V*C

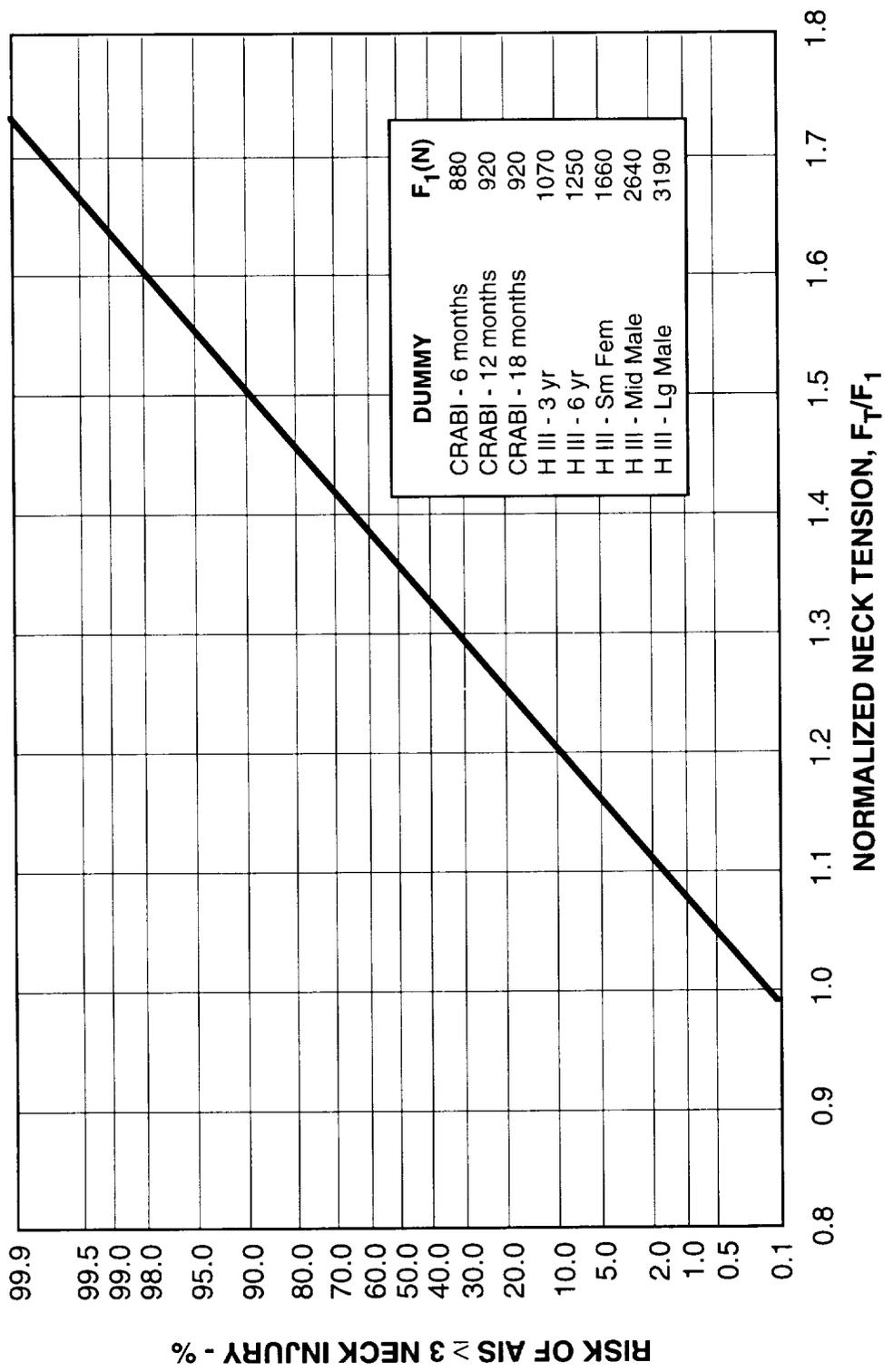


Figure E-7. Risk of AIS \geq 3 Neck Injury for the CRABI and Hybrid III Dummy Families as a Function of Normalized Neck Tension for Tension-Extension Loading of the Neck

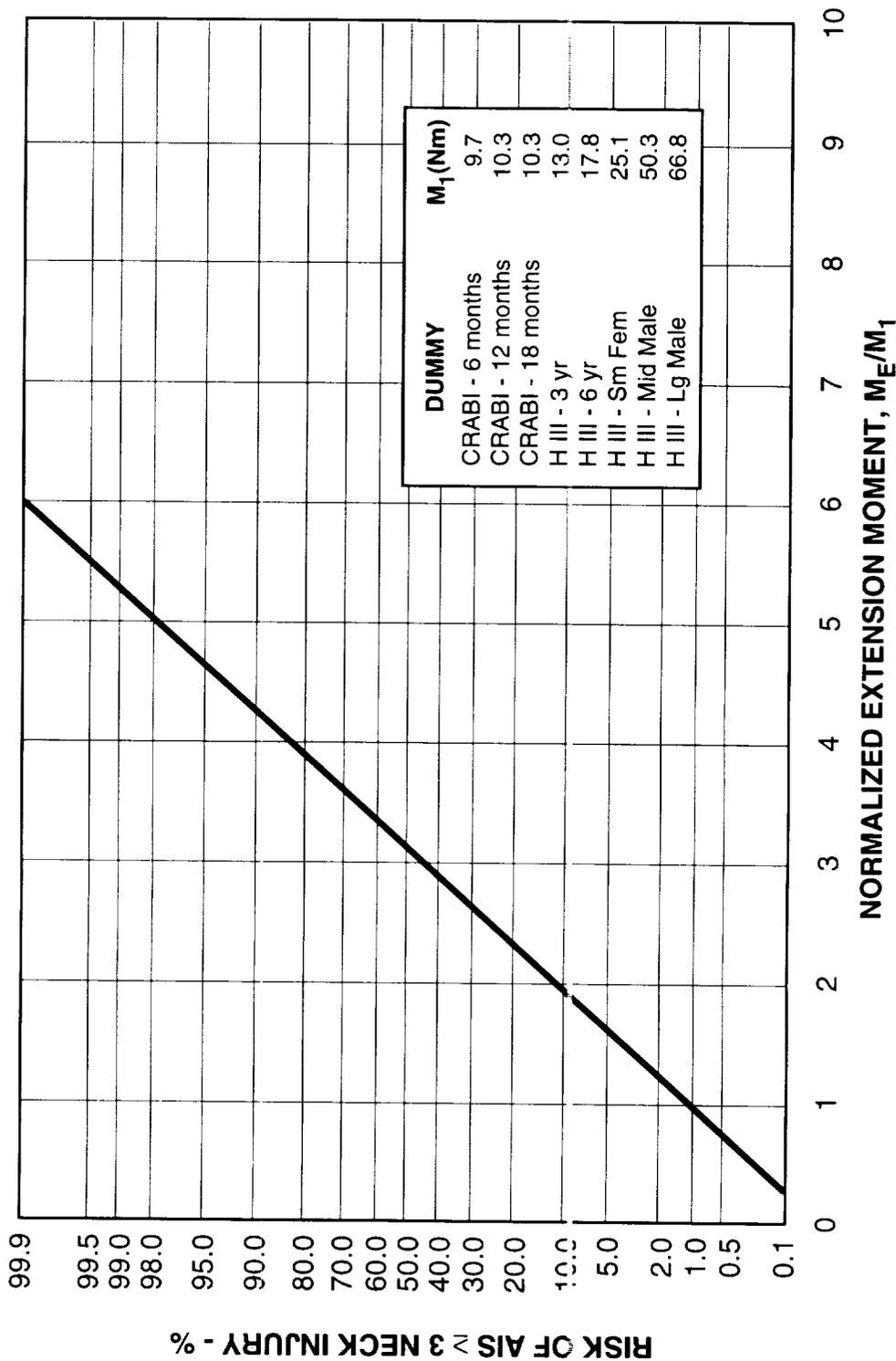


Figure E-8. Risk of AIS ≥ 3 Neck Injury for the CRABI and Hybrid III Dummy Families as a Function of Normalized Neck Extension Moment for Tension-Extension Loading of the Neck

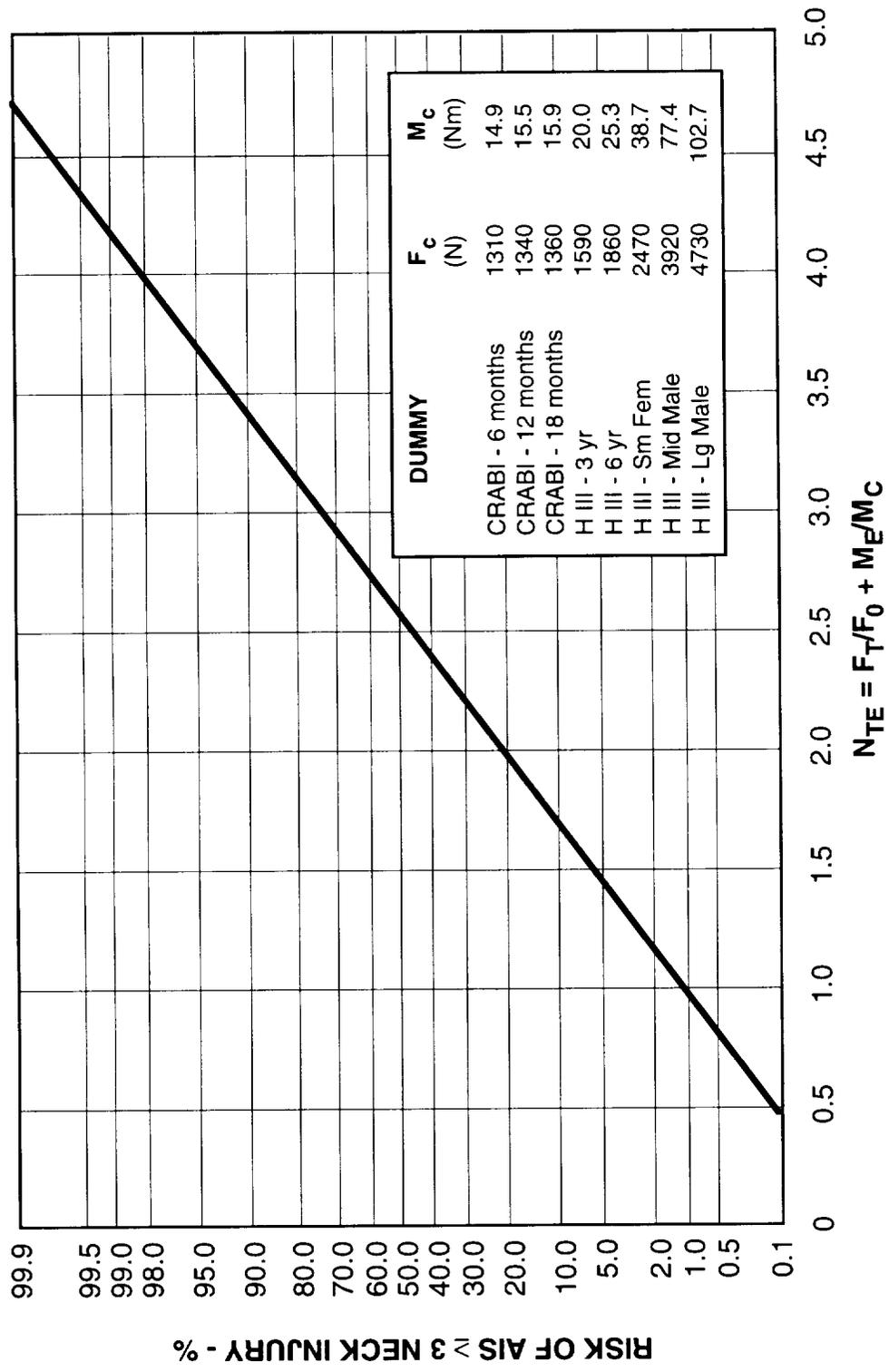
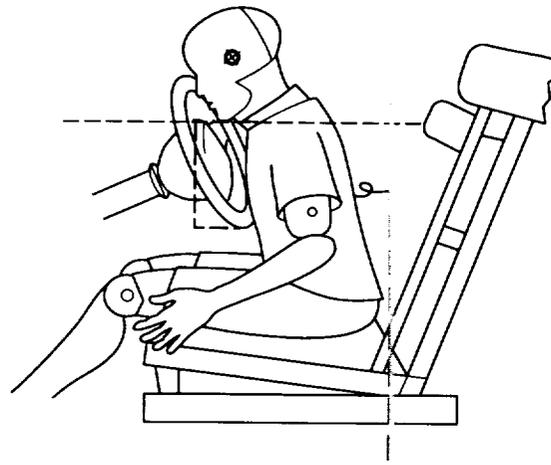
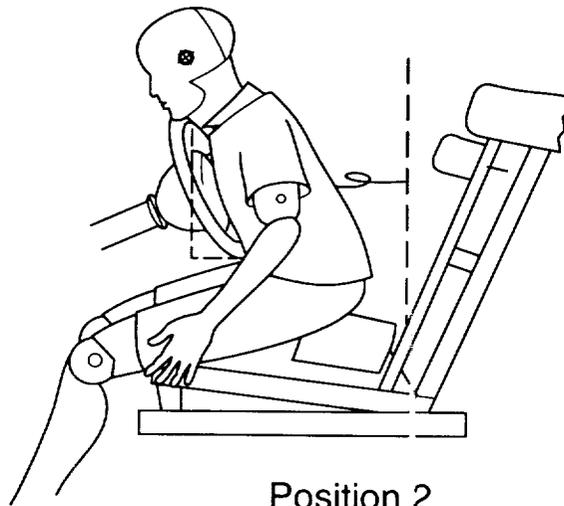


Figure E-9. Neck Injury Risk as a Function of Combined Normalized Neck Extension Moment and Tension



Position 1



Position 2

Figure E-10. Out-of-Position (OOP) Placement in Driver's Seat for 5% Female Hybrid III for Static Air Bag Deployment Tests

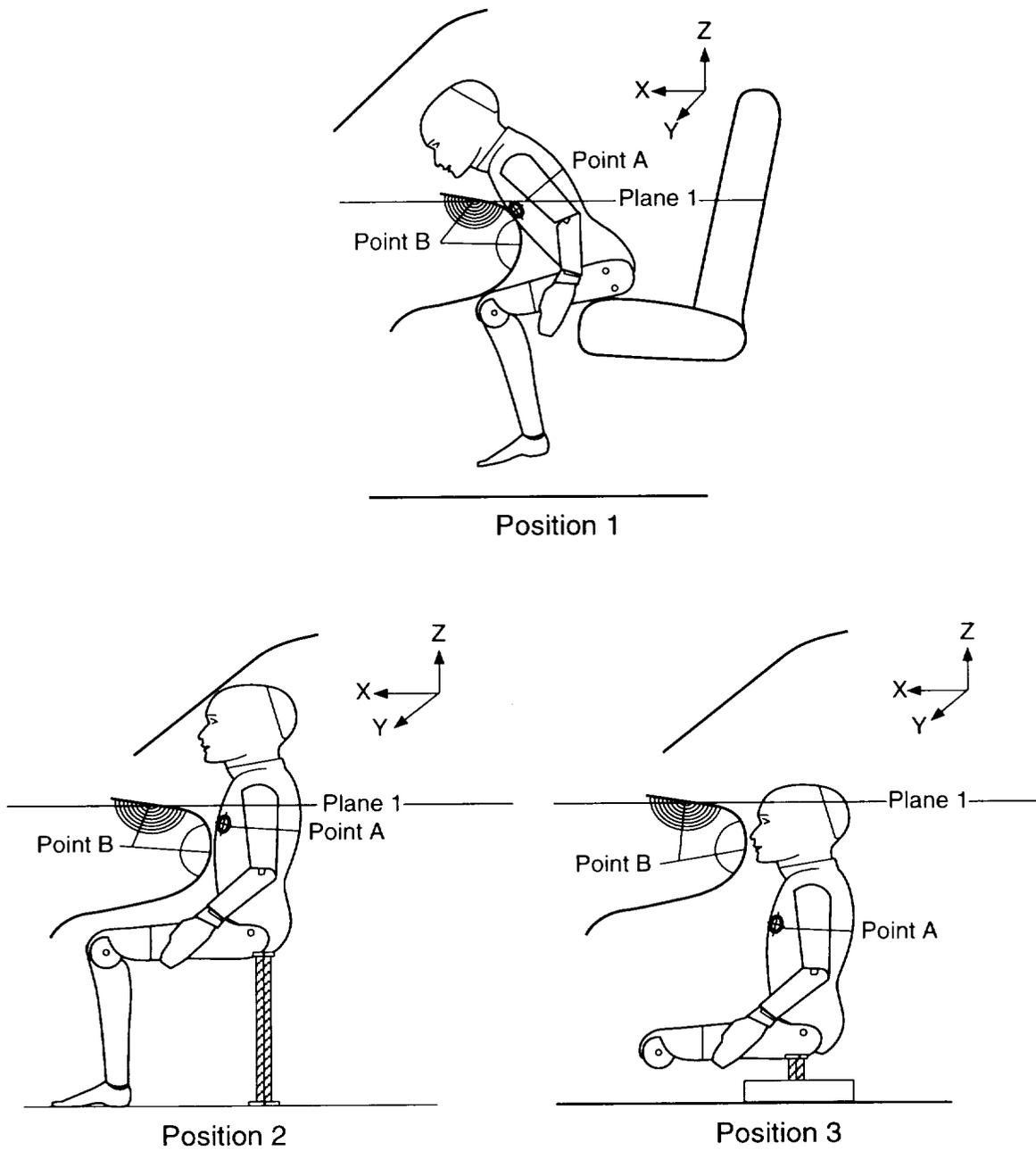


Figure E-11. Out-of-Position (OOP) Placement for Six-Year-Old Child Hybrid III Dummy for Static Air Bag Deployment Tests

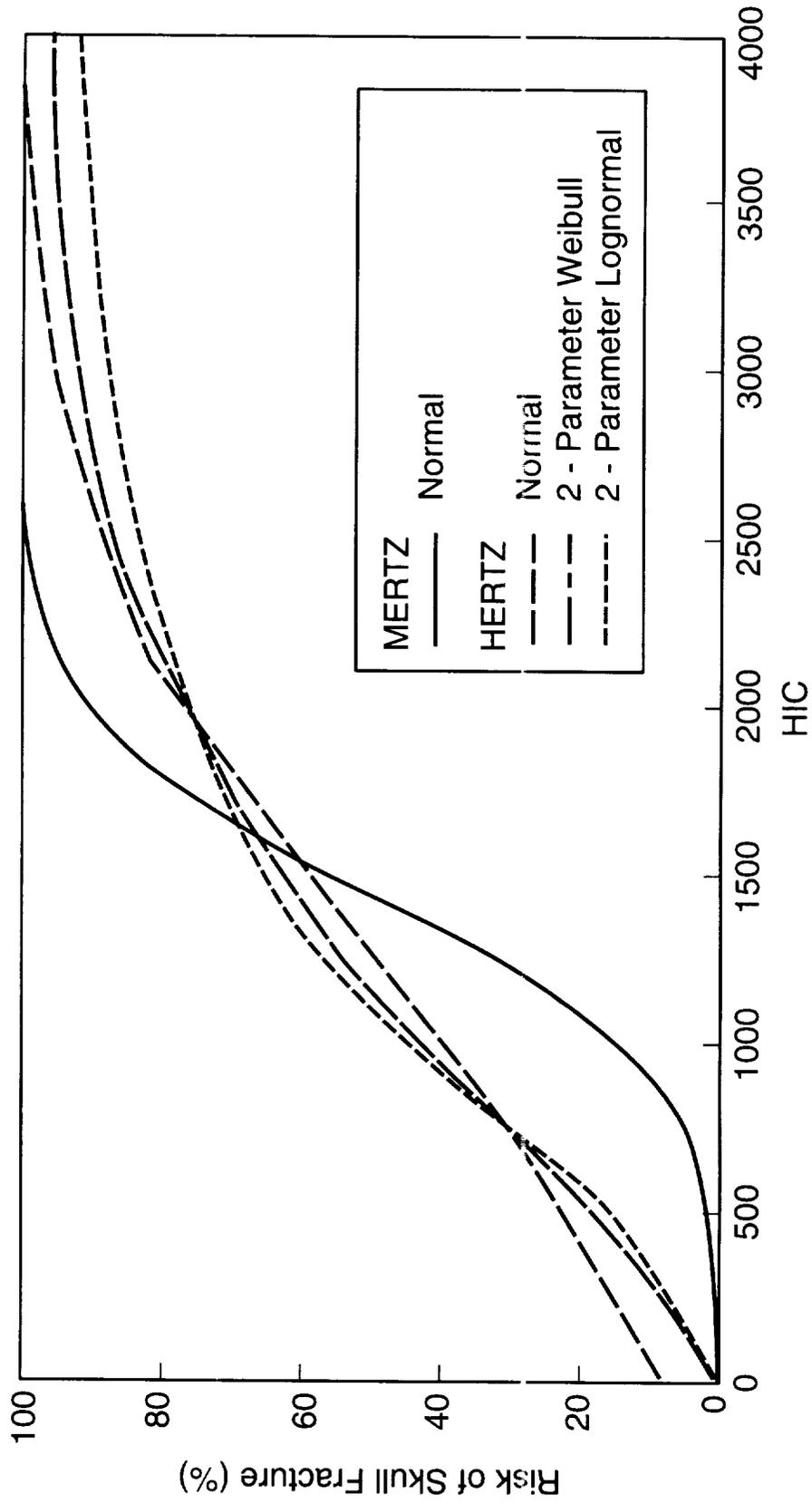


Figure E-12. Head Impact Risk Curves of Prasad and Mertz Compared to Risk Curves Developed by Hertz

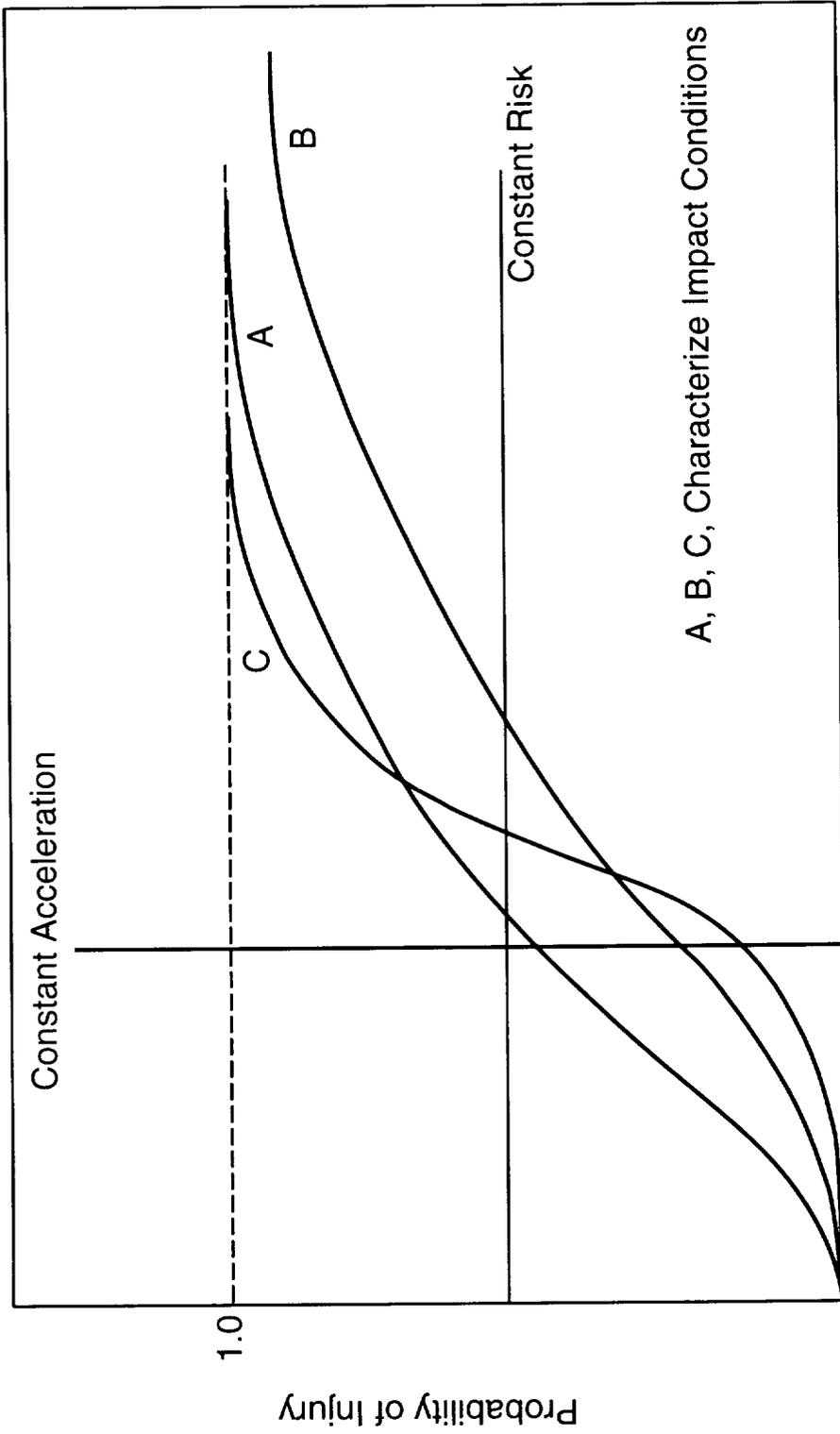


Figure E-13. Effect of Spinal Acceleration on Injury

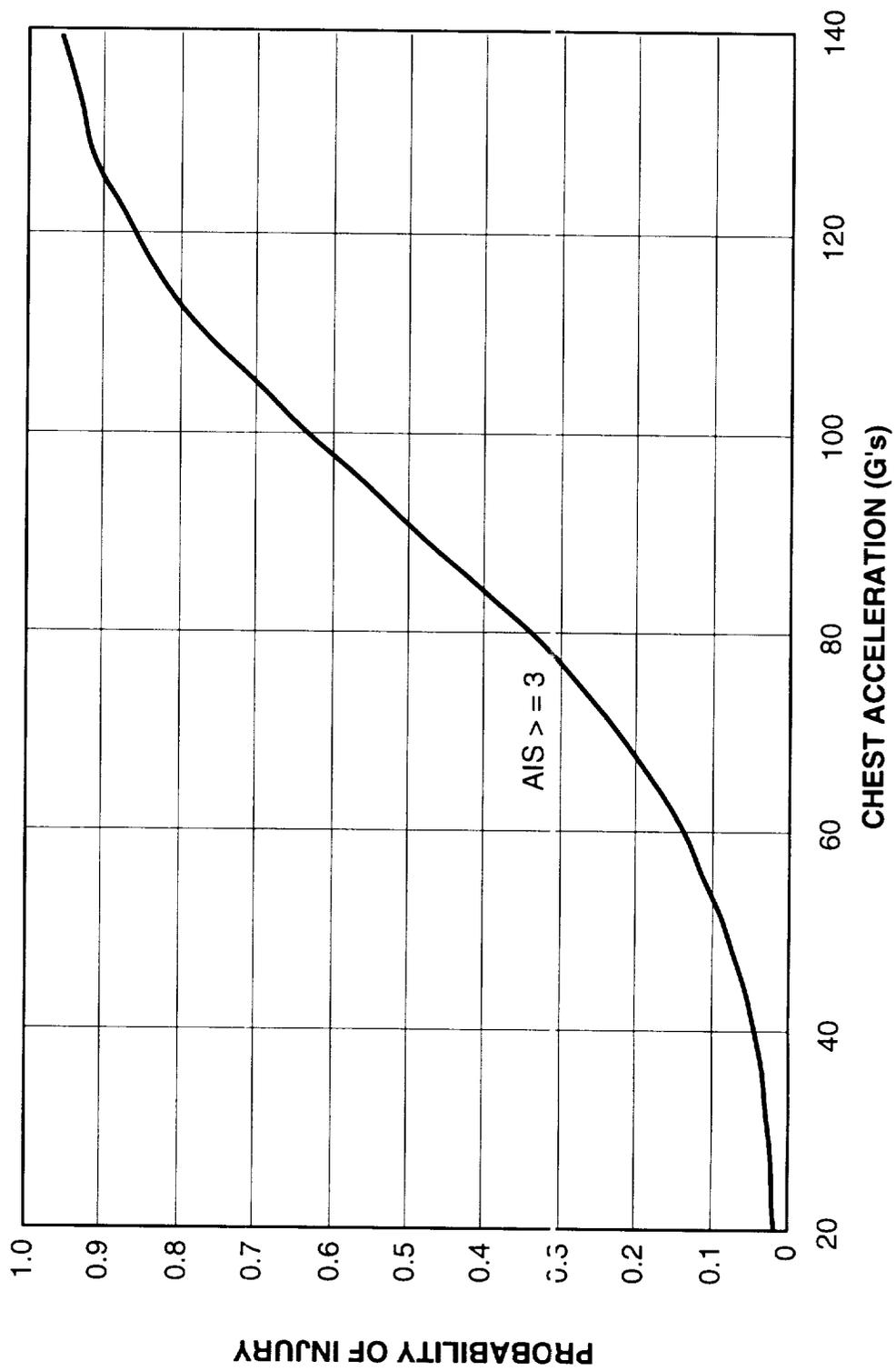


Figure E-14. Probability of Injury vs. Chest Acceleration with Air Bag Restraints (Age Adjusted)

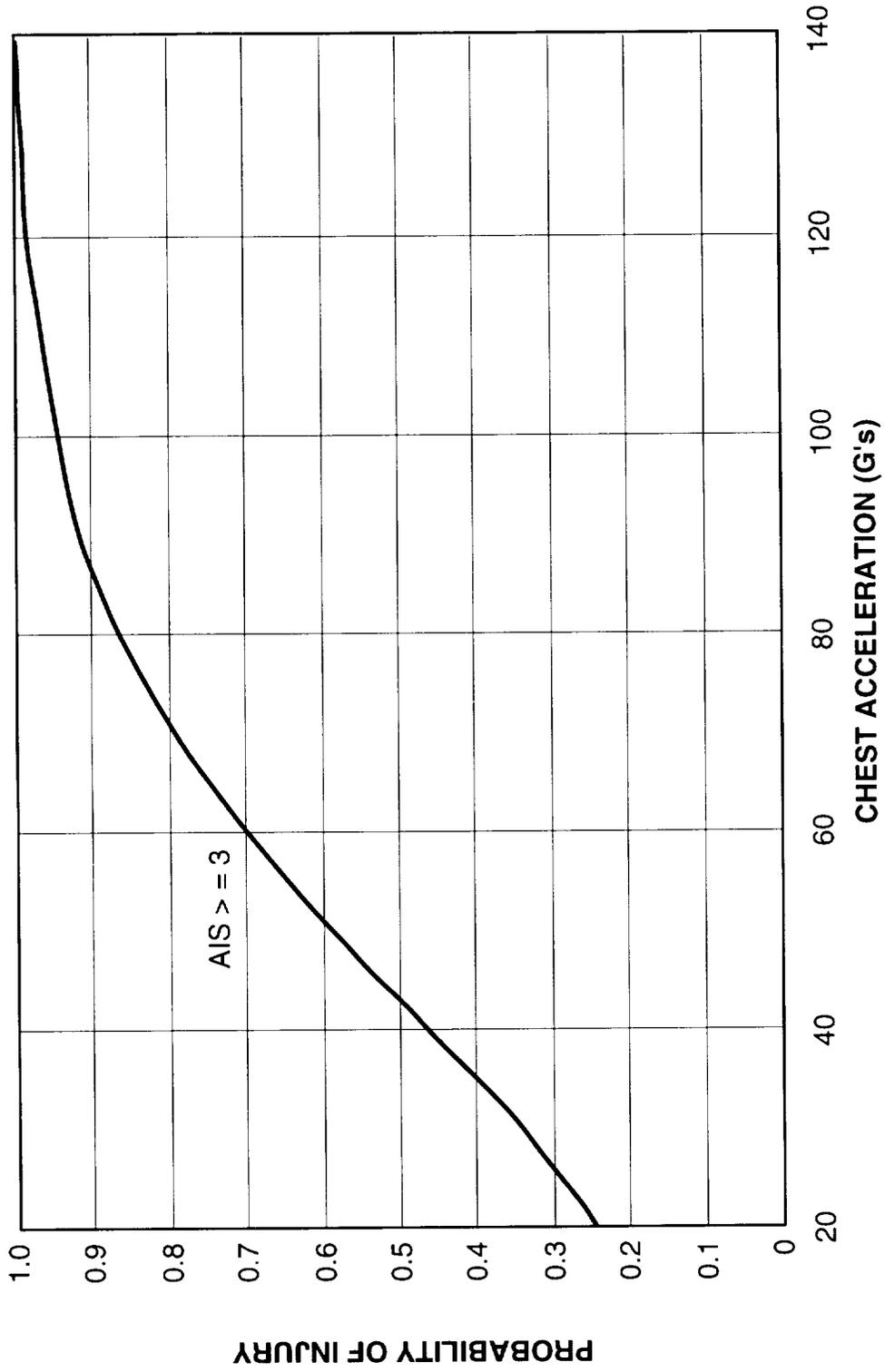


Figure E-15. Probability of Injury vs. Chest Acceleration Belt Restraints (Age Adjusted)

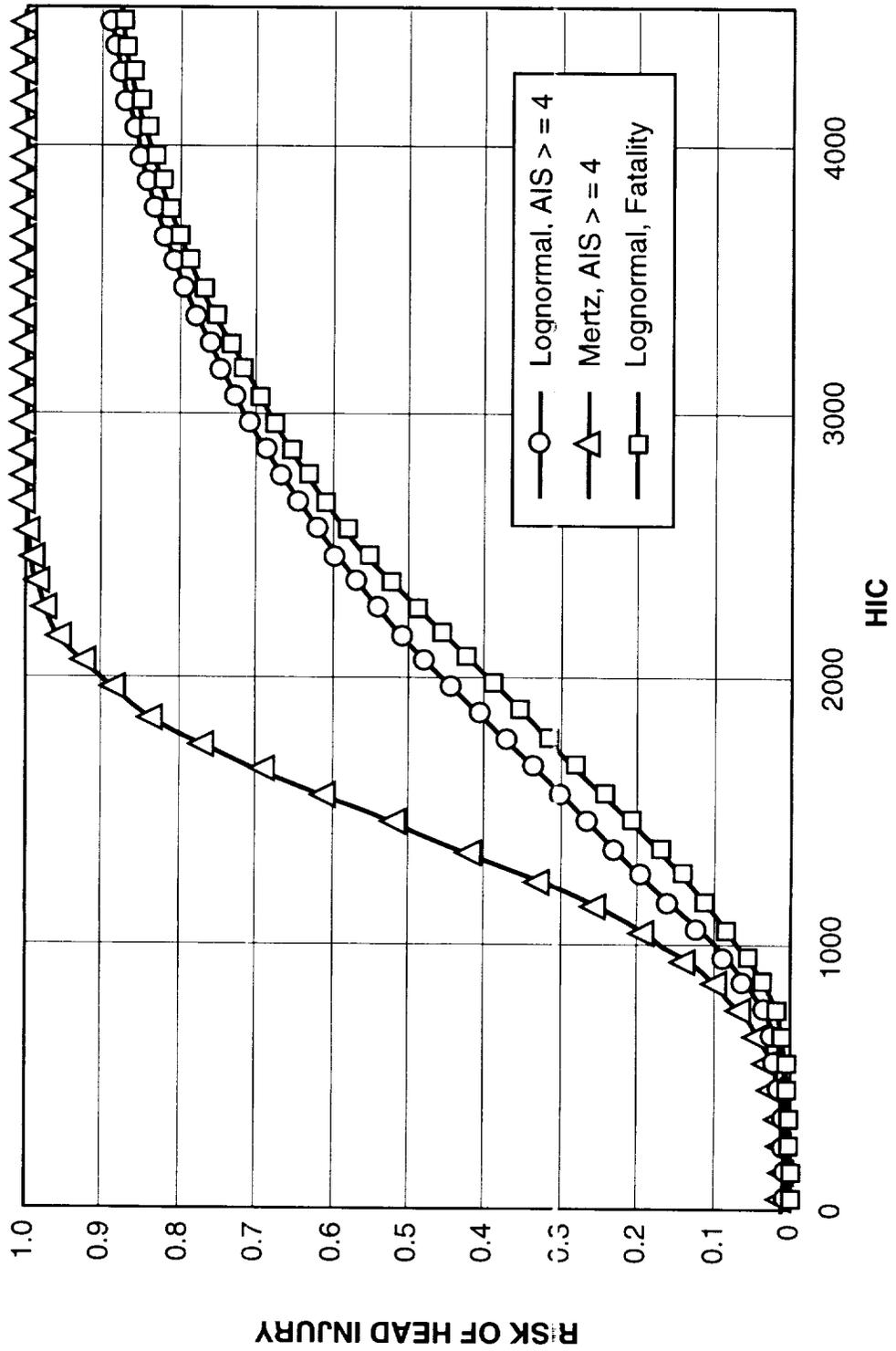


Figure E-16. Head Injury Risk Curves as a Function of HIC

APPENDIX F—INJURY RISK TEST AND SIMULATION DATA

Table F-1a. Head Responses of 5% Female Hill Dummy Driver and Head Injury Risk in 48-km/h (30-mph) Rigid Frontal Barrier [RFB(30) Vehicle Crash Tests Performed by Transport Canada

TC Test Number	Test Vehicle	Barrier Type (mph)	Restraint System	Dummy Type/ Position	Resultant Head Accel., g	HIC	HIC 36	HIC 15	Head Injury Risk (%)
TC96-101	A-96	RFB(30)	3PB+AB	5F/Near	82.9/97.6*	872	872	700	4.4
TC96-102	B-96	RFB(30)	3PB+AB	5F/Near	58.4	353	353	283	0.4
TC96-103	C-96	RFB(30)	3PB+AB	5F/Near	59.3/104*	290	290	268	0.3
TC96-112	D-96	RFB(30)	3PB+AB	5F/Near	67.1	307	307	307	0.4
TC96-114	E-96	RFB(30)	3PB+AB	5F/Near	52.7	245	195	181	0.2
TC96-115	F-96	RFB(30)	3PB+AB	5F/Near	61.9	498	497	309	0.4
TC96-122	G-96	RFB(30)	3PB+AB	5F/Near	39.8	174	65	54	0.1
TC96-151	H-96	RFB(30)	3PB+AB	5F/Near	50.1	259	259	154	0.2
TC96-125	I-96	RFB(30)	3PB	5F/Near	89.8/111.1*	848	848	698	4.3
TC97-101	J-97	RFB(30)	3PB+AB	5F/Near	65.6	443	443	334	0.5
TC97-102	K-97	RFB(30)	3PB+AB	5F/Near	48.6	300	296	209	0.2
TC97-103	L-97	RFB(30)	3PB+AB	5F/Near	41.3	230	115	75	0.1
TC97-104	M-97	RFB(30)	3PB+AB	5F/Near	56.6/129.7*	534	515	313	0.5
TC97-105	N-97	RFB(30)	3PB+AB	5F/Near	42.7	255	255	149	0.1
TC97-107	O-97	RFB(30)	3PB+AB	5F/Near	47.5	230	197	106	0.1
TC97-108	P-97	RFB(30)	3PB	5F/Near	109.9	750	691	384	0.7
TC97-110	E-97	RFB(30)	3PB+AB	5F/Near	50.7	170	170	138	0.1

*Two distinct peak values in order of occurrence
 3PB = Three point lap/shoulder belt
 AB = Air Bag

Table F-1b. Neck Responses of 5% Female Hill Dummy Driver and Neck Injury Risk in 48-km/h (30-mph) Rigid Frontal Barrier [RFB(30)] Vehicle Crash Tests Performed by Transport Canada

TC Test Number	Test Vehicle	Barrier Type (mph)	Restraint System	Dummy Type/ Position	Fore/Aft Positive Shear, N	Fore/Aft Negative Shear, N	Axial Tension, N	Axial Compress., N	Flexion Moment	Extension Moment, Nm	Neck Injury Risk (%)
TC96-101	A-96	RFB(30)	3PB+AB	5F/Near	270	-584.5	2802.5	-1767.8	8.5	-48	37.2
TC96-102	B-96	RFB(30)	3PB+AB	5F/Near	155.5	-2469.5	2710.4	-453.9	6.8	-100.5	94.4
TC96-103	C-96	RFB(30)	3PB+AB	5F/Near	158.9	-2274.7	2612.1	-326.9	11.1	-98.5	92.7
TC96-112	D-96	RFB(30)	3PB+AB	5F/Near	153.8	-1608.2	2593	-387.2	11.3	-75	71.3
TC96-114	E-96	RFB(30)	3PB+AB	5F/Near	529.8	-193.1	1856.7	-603	13.1	-17.1	2.1
TC96-115	F-96	RFB(30)	3PB+AB	5F/Near	205.1	-521.2	1980.5	-1006.1	14.4	-36.2	10.6
TC96-122	G-96	RFB(30)	3PB+AB	5F/Near	223.9	-1080.1	1793.2	-549.1	32.2	-49.2	19.1
TC96-151	H-96	RFB(30)	3PB+AB	5F/Near	294	-358.9	1637.7	-431.6	9.7	-30.6	4.8
TC96-125	I-96	RFB(30)	3PB	5F/Near	213.6	-828.9	2447	-815.7	14.1	-30.4	11.6
TC97-101	J-97	RFB(30)	3PB+AB	5F/Near	N/A	N/A	2120	-276	N/A	N/A	N/A
TC97-102	K-97	RFB(30)	3PB+AB	5F/Near	56	-371	1669	-333	16	-25	3.2
TC97-103	L-97	RFB(30)	3PB+AB	5F/Near	147	-3363	1844	-521	40	-105	89.4
TC97-104	M-97	RFB(30)	3PB+AB	5F/Near	164	-439	1812	-803	26	-28	4.9
TC97-105	N-97	RFB(30)	3PB+AB	5F/Near	176	-156	1593	-403	17	-12	0.9
TC97-107	O-97	RFB(30)	3PB+AB	5F/Near	205	-731	1736	-720	8	-41	11.2
TC97-108	P-97	RFB(30)	3PB	5F/Near	140	-1164	2399	-308	28	-40	19.4
TC97-110	E-97	RFB(30)	3PB+AB	5F/Near	277	-301	1469	-521	19	-24	2.2

3PB = Three point lap/shoulder belt

AB = Air Bag

Table F-1c. Chest Responses of 5% Female Hill Dummy Driver and Chest Injury Risk in 48-km/h (30-mph) Rigid Frontal Barrier [RFB(30)] Vehicle Crash Tests Performed by Transport Canada

TC Test Number	Test Vehicle	Barrier Type (mph)	Restraint System	Dummy Type/ Position	Mid-Sternum Deflection, mm	Chest Injury Risk (%) AB ¹ /Belt ²	Mid-Sternum V*C, m/s	Resultant Chest Accel., g
TC96-101	A-96	RFB(30)	3PB+AB	5F/Near	41.4	10.0/30.6	0.5	81
TC96-102	B-96	RFB(30)	3PB+AB	5F/Near	29.8	0.1/11.7	0.27	38.3
TC96-103	C-96	RFB(30)	3PB+AB	5F/Near	22.7	0.0/5.4	0.16	40.2
TC96-112	D-96	RFB(30)	3PB+AB	5F/Near	24.4	0.0/6.6	0.21	48
TC96-114	E-96	RFB(30)	3PB+AB	5F/Near	21.2	0.0/4.5	0.09	46.4
TC96-115	F-96	RFB(30)	3PB+AB	5F/Near	30.6	0.2/12.7	0.27	49.5
TC96-122	G-96	RFB(30)	3PB+AB	5F/Near	42.3	12.6/32.5	0.34	49.3
TC96-151	H-96	RFB(30)	3PB+AB	5F/Near	21.7	0.0/4.8	0.08	39.8
TC96-125	I-96	RFB(30)	3PB	5F/Near	39.6	27.0	0.26	51.9
TC97-101	J-97	RFB(30)	3PB+AB	5F/Near	34.7	1.1/18.4	0.36	50.4
TC97-102	K-97	RFB(30)	3PB+AB	5F/Near	48.2	40.2/45.8	0.52	41.2
TC97-103	L-97	RFB(30)	3PB+AB	5F/Near	33.8	0.7/17.0	0.26	48.6
TC97-104	M-97	RFB(30)	3PB+AB	5F/Near	35.1	1.3/19.0	0.27	80.5
TC97-105	N-97	RFB(30)	3PB+AB	5F/Near	34.7	1.1/18.4	0.37	36.8
TC97-107	O-97	RFB(30)	3PB+AB	5F/Near	40.4	7.6/28.6	0.32	48.2
TC97-108	P-97	RFB(30)	3PB	5F/Near	52.7	56.3	0.64	64
TC97-110	E-97	RFB(30)	3PB+AB	5F/Near	29.4	0.0/11.3	0.31	38.7

(1) Injury risk is calculated using AIS \geq 3 rib fractures for distributed chest impacts in Figure E-4 in Appendix E.
(2) Injury risk is calculated using AIS \geq 3 thoracic injury due to shoulder belt loading in Figure E-3 in Appendix E.
3PB = Three point lap/shoulder belt
AB = Air Bag

Table F-2a. Head Responses of 50% Male Hill Dummy Driver and Head Injury Risk in 48-km/h (30-mph) Rigid Frontal Barrier [RFB(30)] Vehicle Crash Tests Performed by Transport Canada

TC Test Number	Test Vehicle	Barrier Type (mph)	Restraint System	Dummy Type/ Position	Resultant Head Accel., g	HIC	HIC 36	HIC 15	Head Injury Risk (%)
TC96-102	B-96	RFB(30)	3PB+AB	50M/Normal	48.6	208	199	167	0.2
TC96-103	C-96	RFB(30)	3PB+AB	50M/Normal	37.5	179	167	95	0.1
TC96-112	D-96	RFB(30)	3PB+AB	50M/Normal	38.2	169	169	112	0.1
TC96-114	E-96	RFB(30)	3PB+AB	50M/Normal	54.2	364	364	237	0.3
TC96-115	F-96	RFB(30)	3PB+AB	50M/Normal	49.6	328	320	191	0.2
TC96-125	G-96	RFB(30)	3PB	50M/Normal	46	338	325	172	0.2
TC96-151	H-96	RFB(30)	3PB+AB	50M/Normal	45	241	241	161	0.2

3PB = Three point lap/shoulder belt
AB = Air Bag

**Table F-2b. Neck Responses of 50% Male Hill Dummy Driver and Neck Injury Risk in 48-km/h (30-mph) Rigid Frontal Barrier [RFB(30)]
Vehicle Crash Tests Performed by Transport Canada**

TC Test Number	Test Vehicle	Barrier Type (mph)	Restraint System	Dummy Type/ Position	Fore/Aft Positive Shear, N	Fore/Aft Negative Shear, N	Axial Tension, N	Axial Compress., N	Flexion Moment	Extension Moment, Nm	Neck Injury Risk (%)
TC96-102	B-96	RFB(30)	3PB+AB	50M/Normal	1107.4	-299.1	352.3	-1139.4	99.1	-7.9	0.0
TC96-103	C-96	RFB(30)	3PB+AB	50M/Normal	282	-415.3	1212.4	-444.3	35.6	-12.2	0.0
TC96-112	D-96	RFB(30)	3PB+AB	50M/Normal	664.8	-555.4	1120.4	-599.9	42.5	-22.8	0.2
TC96-114	E-96	RFB(30)	3PB+AB	50M/Normal	570.8	-652.8	1256.8	-336.4	52.3	-16.5	0.1
TC96-115	F-96	RFB(30)	3PB+AB	50M/Normal	606.7	-252.9	1571	-672.9	22.7	-14.7	0.2
TC96-125	G-96	RFB(30)	3PB+AB	50M/Normal	317.9	-687	1805.9	-425.3	36.9	-21	0.3
TC96-151	H-96	RFB(30)	3PB+AB	50M/Normal	721.2	-446	1085.4	-412.6	50.5	-8.1	0.0

3PB = Three point lap/shoulder belt
AB = Air Bag

Table F-2c. Chest Responses of 50% Male Hill Dummy Driver and Chest Injury Risk in 48-km/h (30-mph) Rigid Frontal Barrier [RFB(30)] Vehicle Crash Tests Performed by Transport Canada

TC Test Number	Test Vehicle	Barrier Type (mph)	Restraint System	Dummy Type/Position	Mid-Sternum Deflection, mm	Chest Injury Risk (%) AB ¹ /Belt ²	Mid-Sternum V*C, m/s	Resultant Chest Accel., g
TC96-102	B-96	RFB(30)	3PB+AB	50M/Normal	15.5	0.0/2.1	0.04	36.6
TC96-103	C-96	RFB(30)	3PB+AB	50M/Normal	28.2	0.0/10.0	0.12	32.4
TC96-112	D-96	RFB(30)	3PB+AB	50M/Normal	24.8	0.0/6.9	0.14	41.7
TC96-114	E-96	RFB(30)	3PB+AB	50M/Normal	21.4	0.0/4.6	0.09	72.4
TC96-115	F-96	RFB(30)	3PB+AB	50M/Normal	26.8	0.0/8.6	0.11	49.5
TC96-125	G-96	RFB(30)	3PB+AB	50M/Normal	22.8	0.0/5.5	0.08	70.9
TC96-151	H-96	RFB(30)	3PB+AB	50M/Normal	25.5	0.0/7.5	0.09	40.4

(1) Injury risk is calculated using AIS \geq 3 rib fractures for distributed chest impacts in Figure E-4 in Appendix E.
(2) Injury risk is calculated using AIS \geq 3 thoracic injury due to shoulder belt loading in Figure E-3 in Appendix E.
3PB = Three point lap/shoulder belt
AB = Air Bag

Table F-3a. Head Responses of 5% Female HIII Dummy Driver and Head Injury Risk in 40-, 32-, and 24-km/h (25-, 20-, and 15-mph) Deformable Offset Barrier [DOB(25), DOB(20), DOB(15)] Vehicle Crash Tests Performed by Transport Canada

TC Test Number	Test Vehicle	Barrier Type (mph)	Restraint System	Dummy Type/ Position	Resultant Head Accel., g	HIC	HIC 36	HIC 15	Head Injury Risk (%)
TC95-206	D-95	DOB(25)	3PB+AB	5F/Near	74.5	367	367	367	0.7
TC96-209	D-96	DOB(25)	3PB	5F/Near	45.1	189	189	189	0.2
TC96-211	B-96	DOB(25)	3PB+AB	5F/Near	82.9	650	457	338	0.5
TC96-210	B-96	DOB(25)	3PB	5F/Near	54.1	254	254	235	0.3
TC96-202	B-96	DOB(20)	3PB	5F/Near	55.5	190	190	190	0.2
TC96-204	B-96	DOB(15)	3PB	5F/Near	62.7	206	206	206	0.2
TC96-002	F-96	DOB(25)	3PB+AB	5F/Near	42.5	90	90	85	0.1
TC96-205	F-96	DOB(25)	3PB	5F/Near	49.2	238	238	191	0.2
TC95-021	G-95	DOB(20)	3PB+AB	5F/Near	116.3	548	548	490	1.4
TC95-127	G-96	DOB(20)	3PB	5F/Near	46.2	124	124	124	0.1
TC96-025	E-96	DOB(25)	3PB+AB	5F/Near	47.6	115	115	112	0.1
TC96-207	E-96	DOB(25)	3PB	5F/Near	52.6	134	134	131	0.1
TC96-024	Q-96	DOB(25)	3PB+AB	5F/Near	71.7	321	321	240	0.3
TC96-021	A-96	DOB(25)	3PB+AB	5F/Near	93.2	681	681	648	3.4
TC97-200	D-97-D	DOB(25)	3PB+AB	5F/Near	50.4	N/A	N/A	N/A	N/A

3PB = Three point lap/shoulder belt
 AB = Air Bag

Table F-3b. Neck Responses of 5% Female Hill Dummy Driver and Neck Injury Risk in 40-, 32-, and 24-km/h (25-, 20-, and 15-mph) Deformable Offset Barrier [DOB(25), DOB(20), DOB(15)] Vehicle Crash Tests Performed by Transport Canada

TC Test Number	Test Vehicle	Barrier Type (mph)	Restraint System	Dummy Type/Position	Fore/Aft Positive Shear, N	Fore/Aft Negative Shear, N	Axial Tension, N	Axial Compress., N	Flexion Moment	Extension Moment, Nm	Neck Injury Risk (%)
TC95-206	D-95	DOB(25)	3PB+AB	5F/Near	224	-2977	2752	-505	17	-124	99.4
TC96-209	D-96	DOB(25)	3PB	5F/Near	154	-473	978	-355	16	-14	0.4
TC96-211	B-96	DOB(25)	3PB+AB	5F/Near	217	-3500	4583	-644	11	-134	100.0
TC96-210	B-96	DOB(25)	3PB	5F/Near	157	-444	527	-321	16	-21	0.4
TC96-202	B-96	DOB(20)	3PB	5F/Near	217	-487	790	-470	10	-18	0.4
TC96-204	B-96	DOB(15)	3PB	5F/Near	282	-320	644	-597	18	-11	0.1
TC96-002	F-96	DOB(25)	3PB+AB	5F/Near	205	-292	1225	-229	19	-17	0.8
TC96-205	F-96	DOB(25)	3PB	5F/Near	135	-559	892	-279	14	-8	0.2
TC95-021	G-95	DOB(20)	3PB+AB	5F/Near	234	-991	4170	-425	15	-45	64.2
TC95-127	G-96	DOB(20)	3PB	5F/Near	186	-620	809	-501	24	-9	0.2
TC96-025	E-96	DOB(25)	3PB+AB	5F/Near	215	-402	1330	-270	23	-24	1.8
TC96-207	E-96	DOB(25)	3PB	5F/Near	89	-564	978	-235	33	-7	0.2
TC96-024	Q-96	DOB(25)	3PB+AB	5F/Near	152	-1605	2676	-308	5	-67	62.2
TC96-021	A-96	DOB(25)	3PB+AB	5F/Near	436	-979	3044	-705	20	-53	50.1
TC97-200	D-97-D	DOB(25)	3PB+AB	5F/Near	N/A	N/A	902	80	17.7	-38.1	3.5

3PB = Three point lap/shoulder belt
 AB = Air Bag

Table F-3c. Chest Responses of 5% Female Hill Dummy Driver and Chest Injury Risk in 40-, 32-, and 24-km/h (25-, 20-, and 15-mph) Deformable Offset Barrier [DOB(25), DOB(20), DOB(15)] Vehicle Crash Tests Performed by Transport Canada

TC Test Number	Test Vehicle	Barrier Type (mph)	Restraint System	Dummy Type/ Position	Mid-Sternum Deflection, mm	Chest Injury Risk (%) AB/Belt ²	Mid-Sternum V*C, m/s	Resultant Chest Accel., g
TC95-206	D-95	DOB(25)	3PB+AB	5F/Near	22.4	0.0/5.2	0.17	42.4
TC96-209	D-96	DOB(25)	3PB	5F/Near	20.6	4.2/4.2	0.09	28.8
TC96-211	B-96	DOB(25)	3PB+AB	5F/Near	37.6	3.2/23.3	0.25	77.8
TC96-210	B-96	DOB(25)	3PB	5F/Near	13.1	1.5/1.5	0.02	22.2
TC96-202	B-96	DOB(20)	3PB	5F/Near	9.9	0.9	0.01	19.7
TC96-204	B-96	DOB(15)	3PB	5F/Near	7.9	0.7	0.01	20.2
TC96-002	F-96	DOB(25)	3PB+AB	5F/Near	23.1	0.0/5.7	0.17	28.2
TC96-205	F-96	DOB(25)	3PB	5F/Near	22.9	5.5	0.05	23.6
TC95-021	G-95	DOB(20)	3PB+AB	5F/Near	25.9	0.0/7.8	0.2	97.7
TC95-127	G-96	DOB(20)	3PB	5F/Near	12.2	1.3	0.02	17.1
TC96-025	E-96	DOB(25)	3PB+AB	5F/Near	21.9	0.0/4.9	0.17	20.6
TC96-207	E-96	DOB(25)	3PB	5F/Near	20	3.9	0.03	21.5
TC96-024	Q-96	DOB(25)	3PB+AB	5F/Near	33.9	0.8/17.2	0.57	58.6
TC96-021	A-96	DOB(25)	3PB+AB	5F/Near	23.1	0.0/5.7	0.07	29.7
TC97-200	D-97-D	DOB(25)	3PB+AB	5F/Near	24.2	0.0/6.4	0.21	25.8

(1) Injury risk is calculated using AIS \geq 3 rib fractures for distributed chest impacts in Figure E-4 in Appendix E.

(2) Injury risk is calculated using AIS \geq 3 thoracic injury due to shoulder belt loading in Figure E-3 in Appendix E.

3PB = Three point lap/shoulder belt

AB = Air Bag

Table F-4. Injury Risk Comparison for Fully Powered Air Bags of Vehicle D-96. Hybrid III 5% Female and 50% Male Drivers are Belted in 48-km/h (30-mph) Rigid Frontal Barrier Vehicle Crash Tests Performed by Transport Canada

	1*	2*	3*	4*
Hybrid III 95% Male				
Hybrid III 50% Male			Head: 0.1% Neck: 0.2% Chest: 0.0 ^A /6.9 ^B %	
Hybrid III 5% Female		Head: 0.4% Neck: 71.3% Chest: 0.0 ^A /6.6 ^B %		
Hybrid III 6-Year-Old				

*1 = Contact with module

*2 = Full forward (Typical position for Hybrid III 5% Female)

*3 = Midposition (Typical position for Hybrid III 50% Male)

*4 = Full rear (Typical position for Hybrid III 95% Male)

(A) Injury risk is calculated using AIS ≥ 3 rib fractures for distributed chest impacts in Figure E-4.

(B) Injury risk is calculated using AIS ≥ 3 thoracic injury due to shoulder belt loading in Figure E-3.

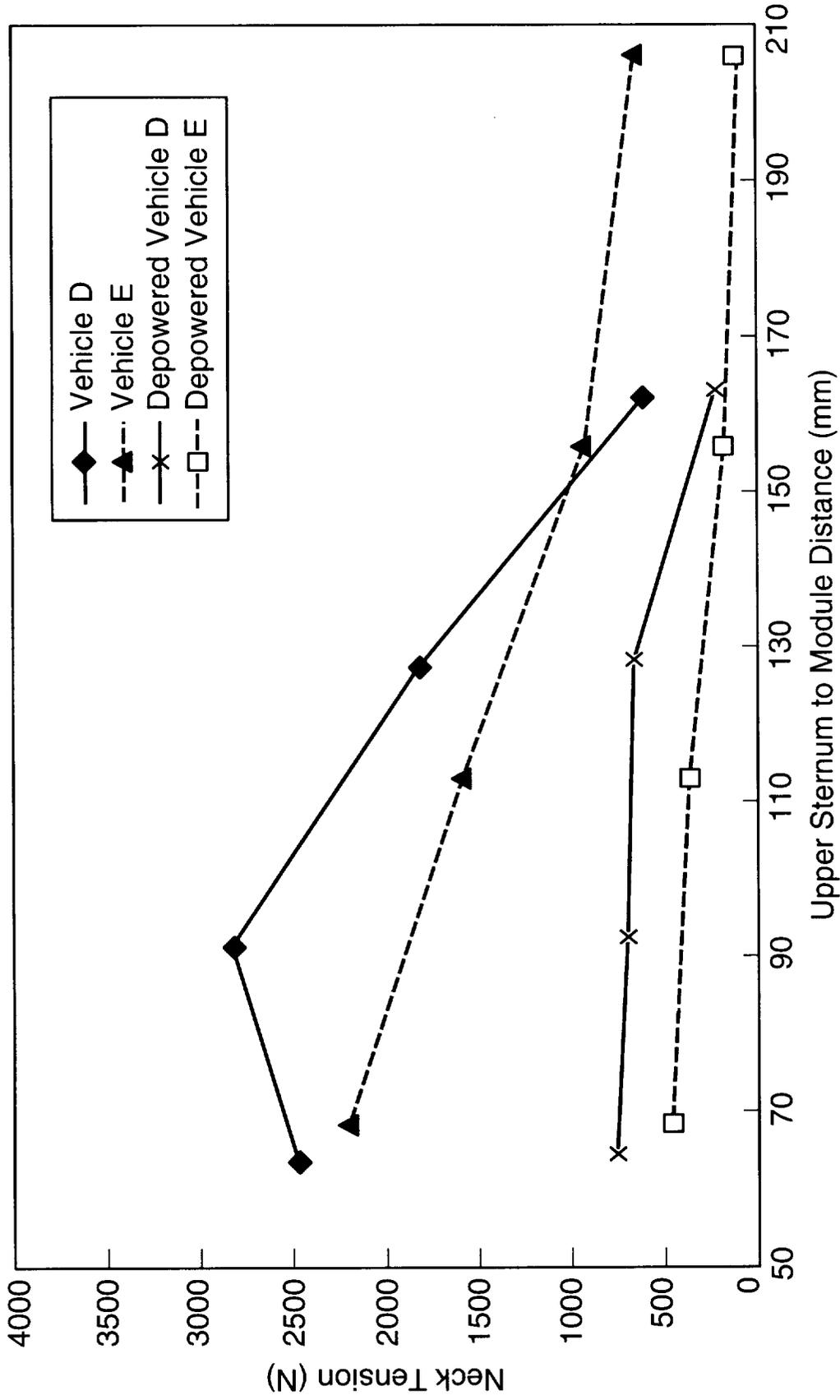


Figure F-1. Neck Tension of 5% Female in Static Out-of-Position Air Bag Deployment Tests as a Function of Sternum-to-Module Distance

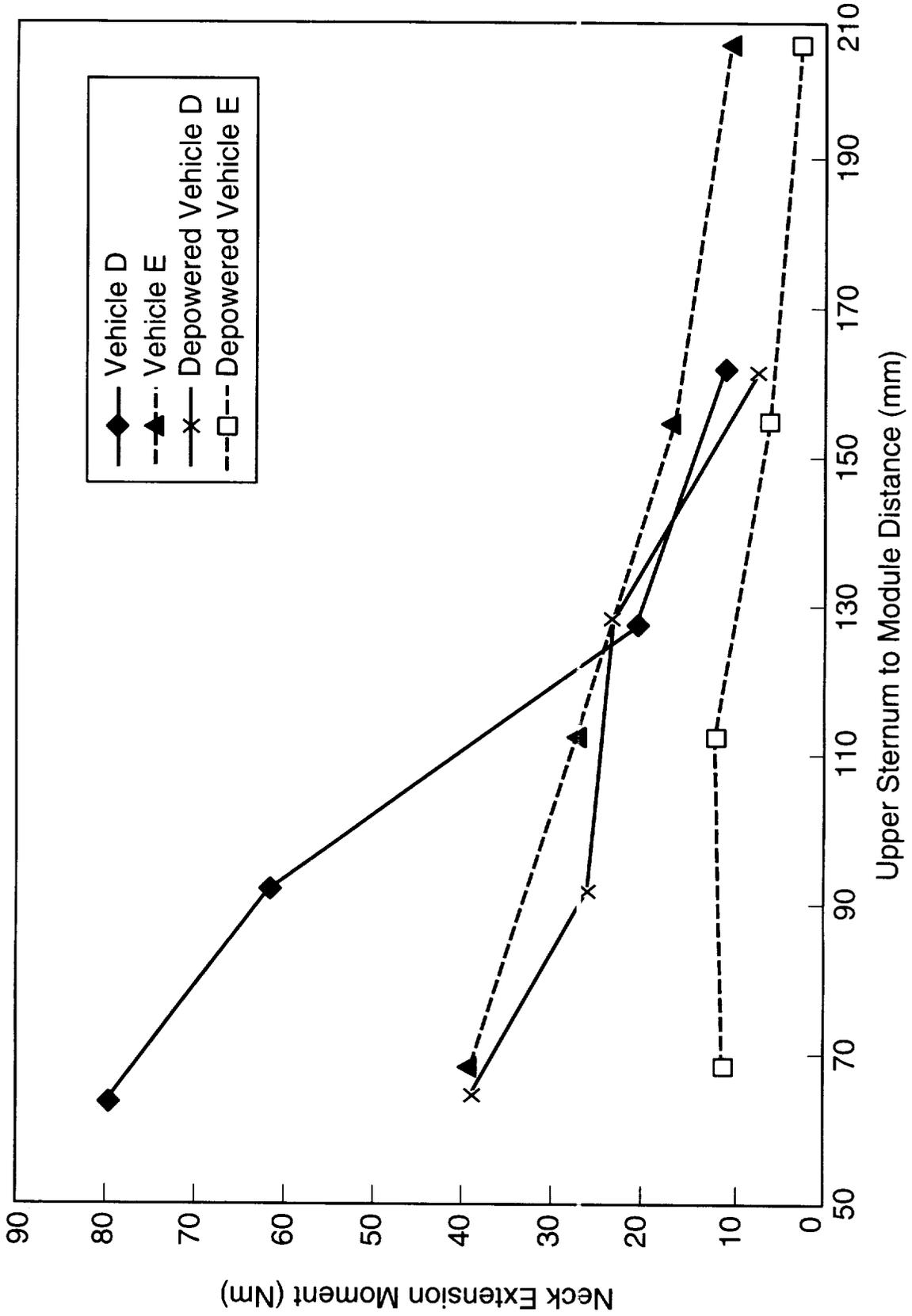


Figure F-2. Neck Extension Moment of 5% Female in Static Out-of-Position Air Bag Deployment Tests as a Function of Sternum-to-Module Distance

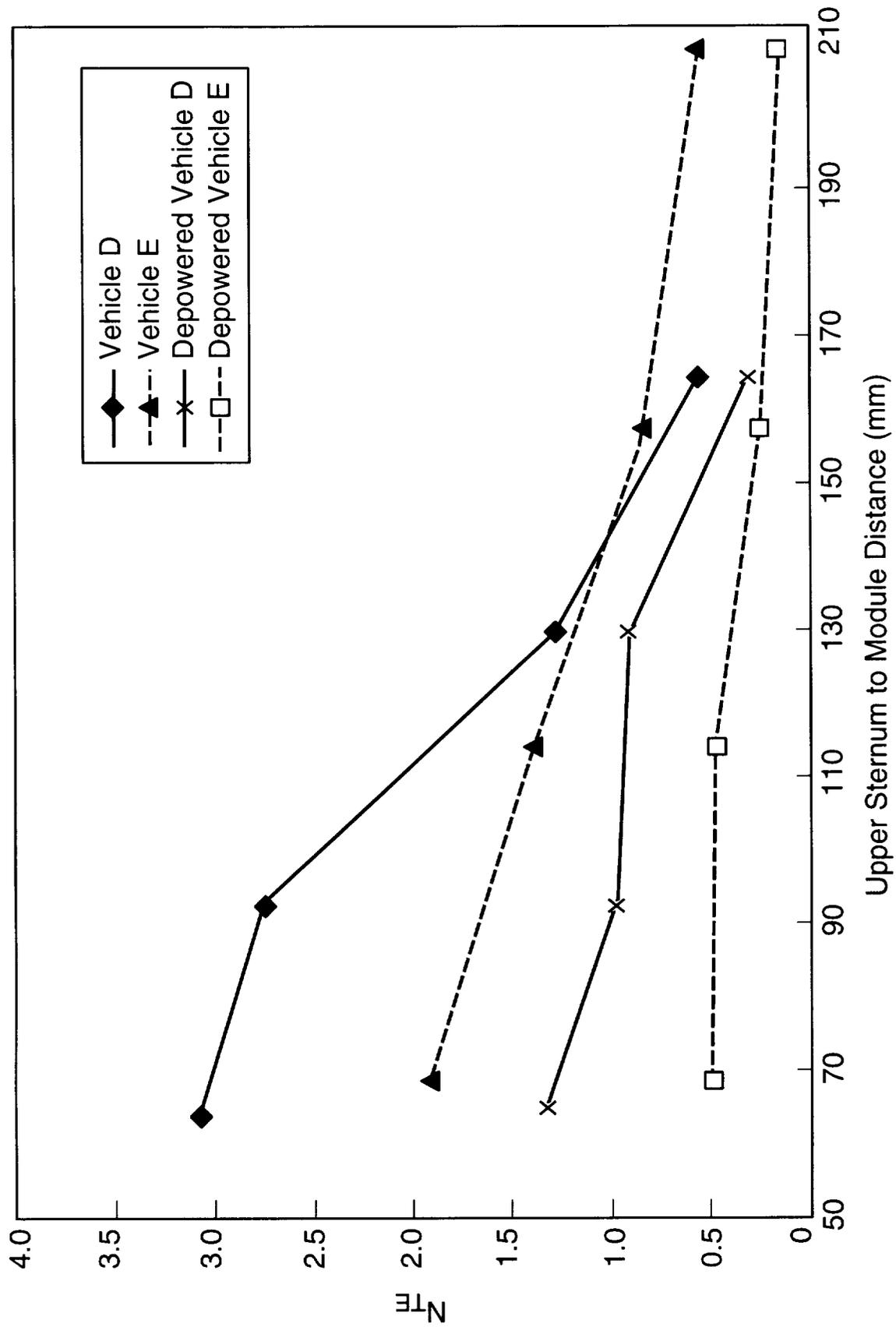


Figure F-3. Normalized Neck Tension and Extension Moment of 5% Female in Static Out-of-Position Air Bag Deployment Tests as a Function of Sternum-to-Module Distance

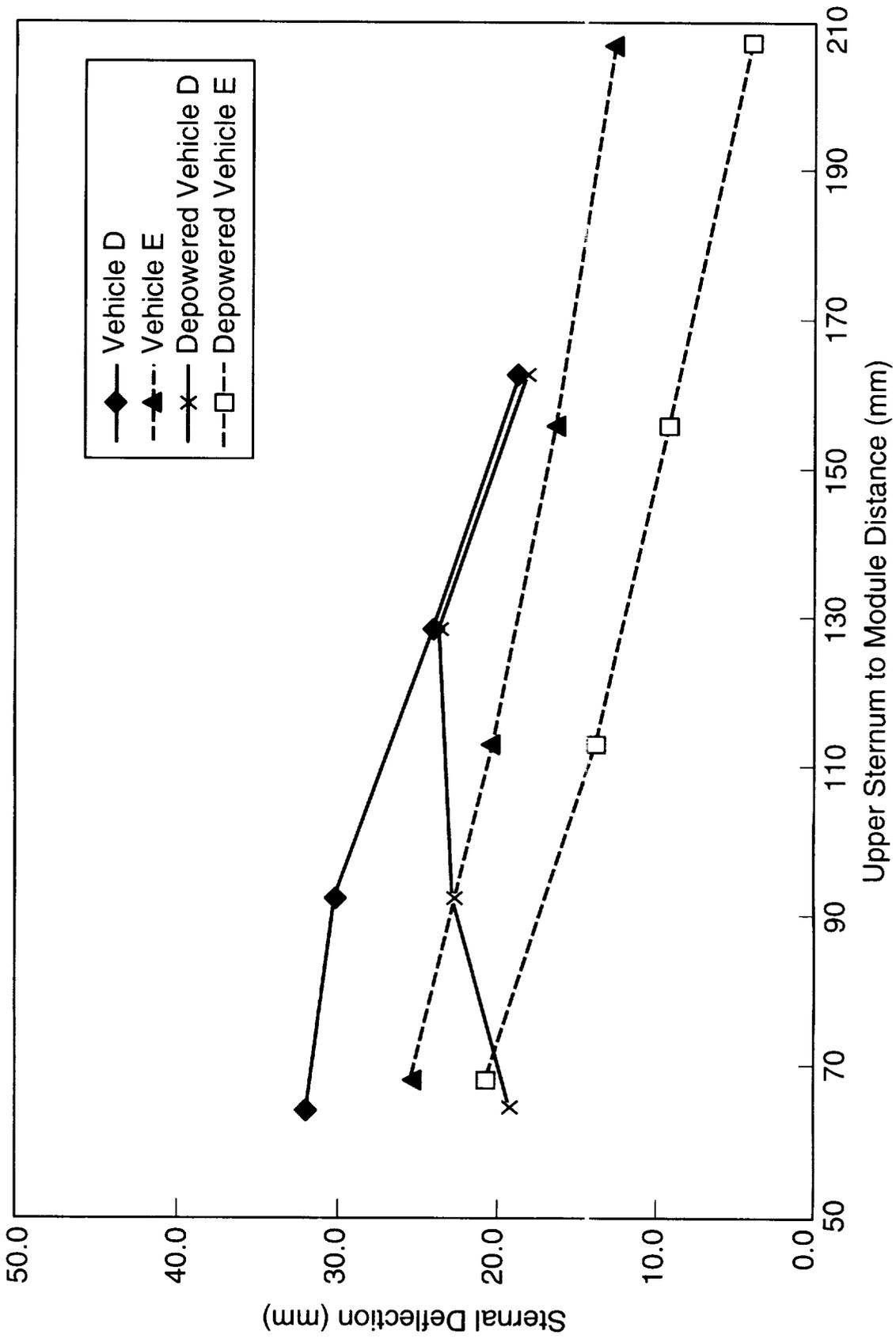


Figure F-4. Sternal Deflection of 5% Female in Static Out-of-Position Air Bag Deployment Tests as a Function of Sternum-to-Module Distance

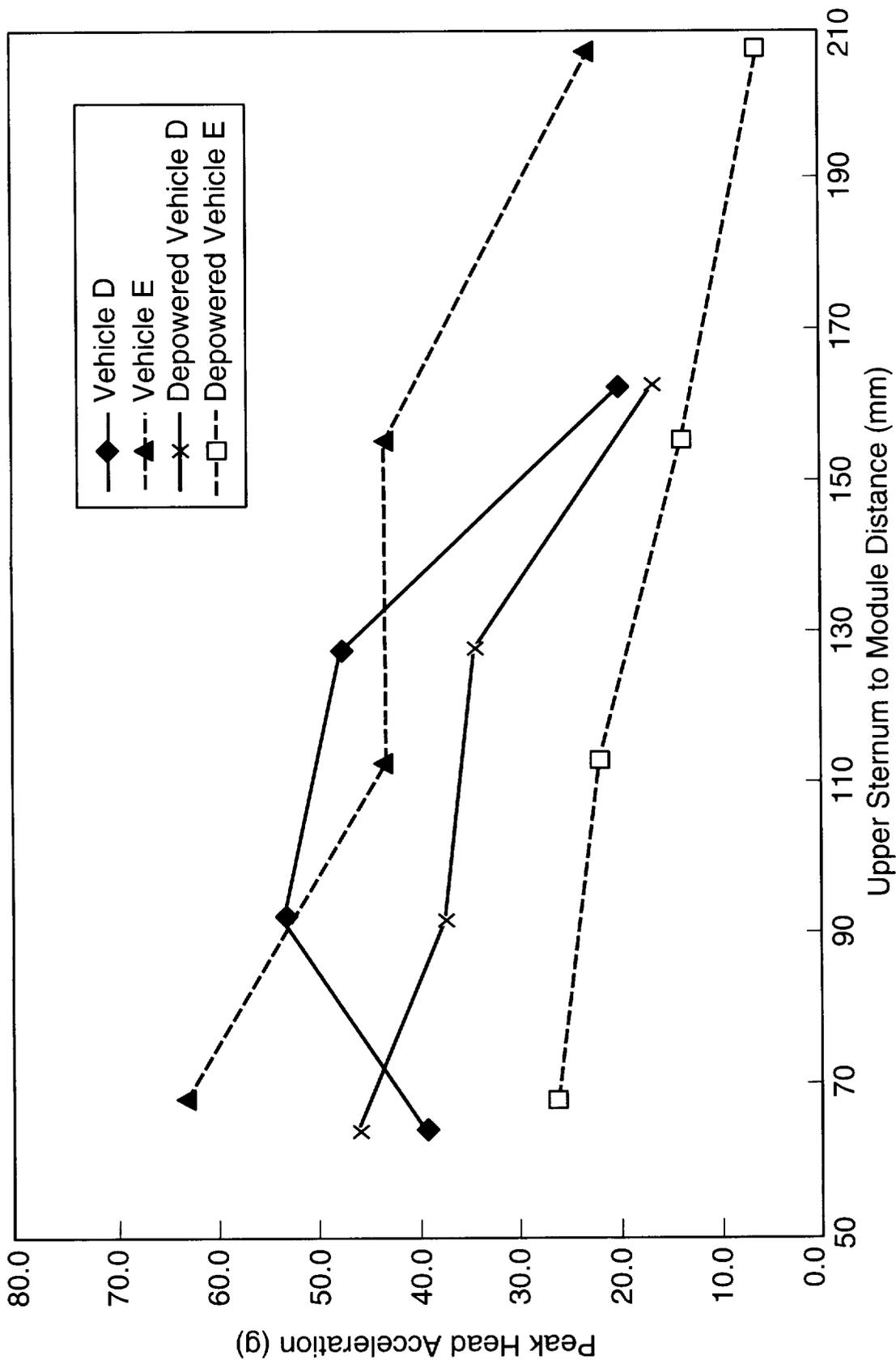


Figure F-5. Peak Head Acceleration of 5% Female in Static Out-of-Position Air Bag Deployment Tests as a Function of Sternum-to-Module Distance

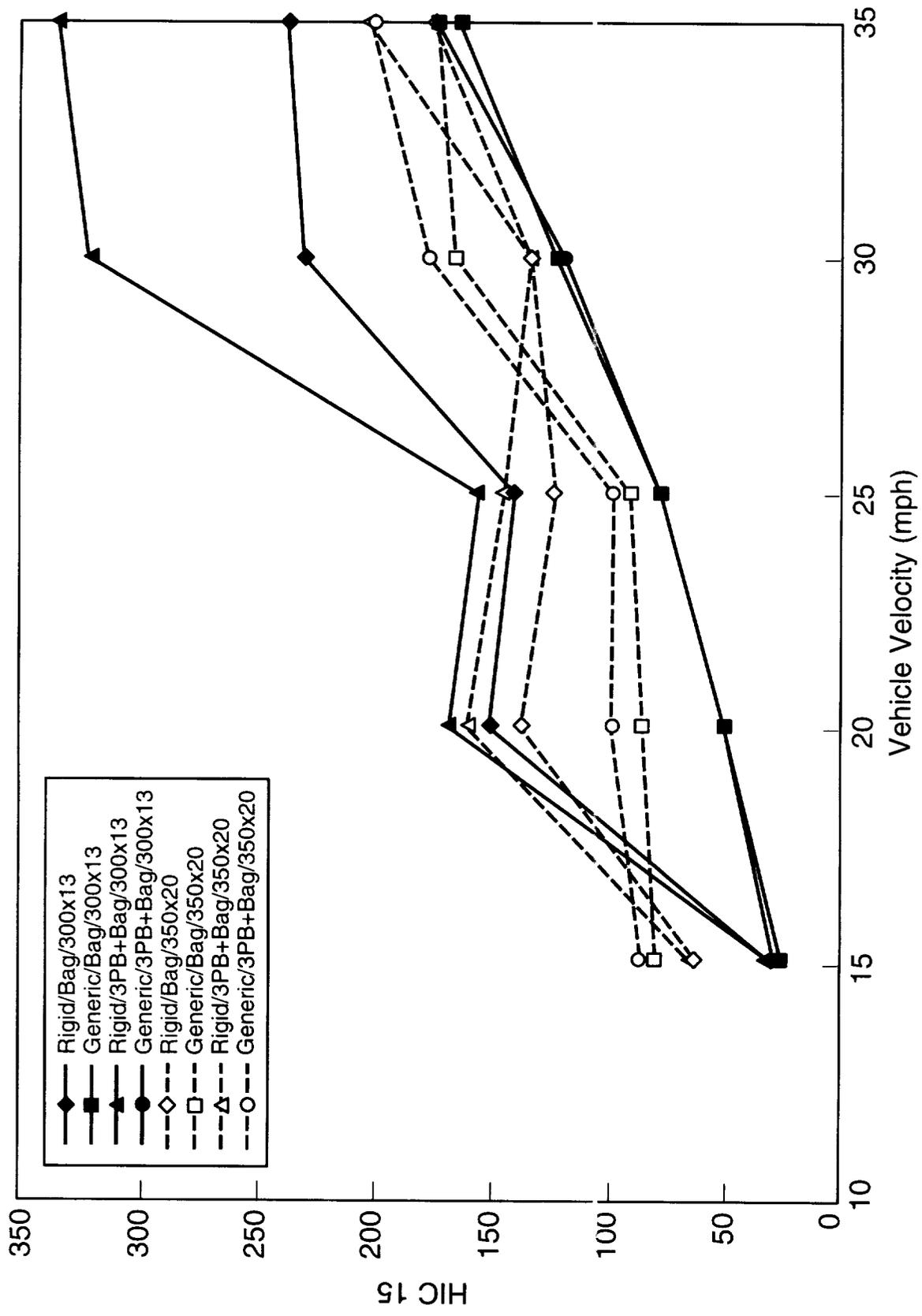


Figure F-6. HIC 15 of 5% Female as a Function of Vehicle Velocity (From Reference [8])

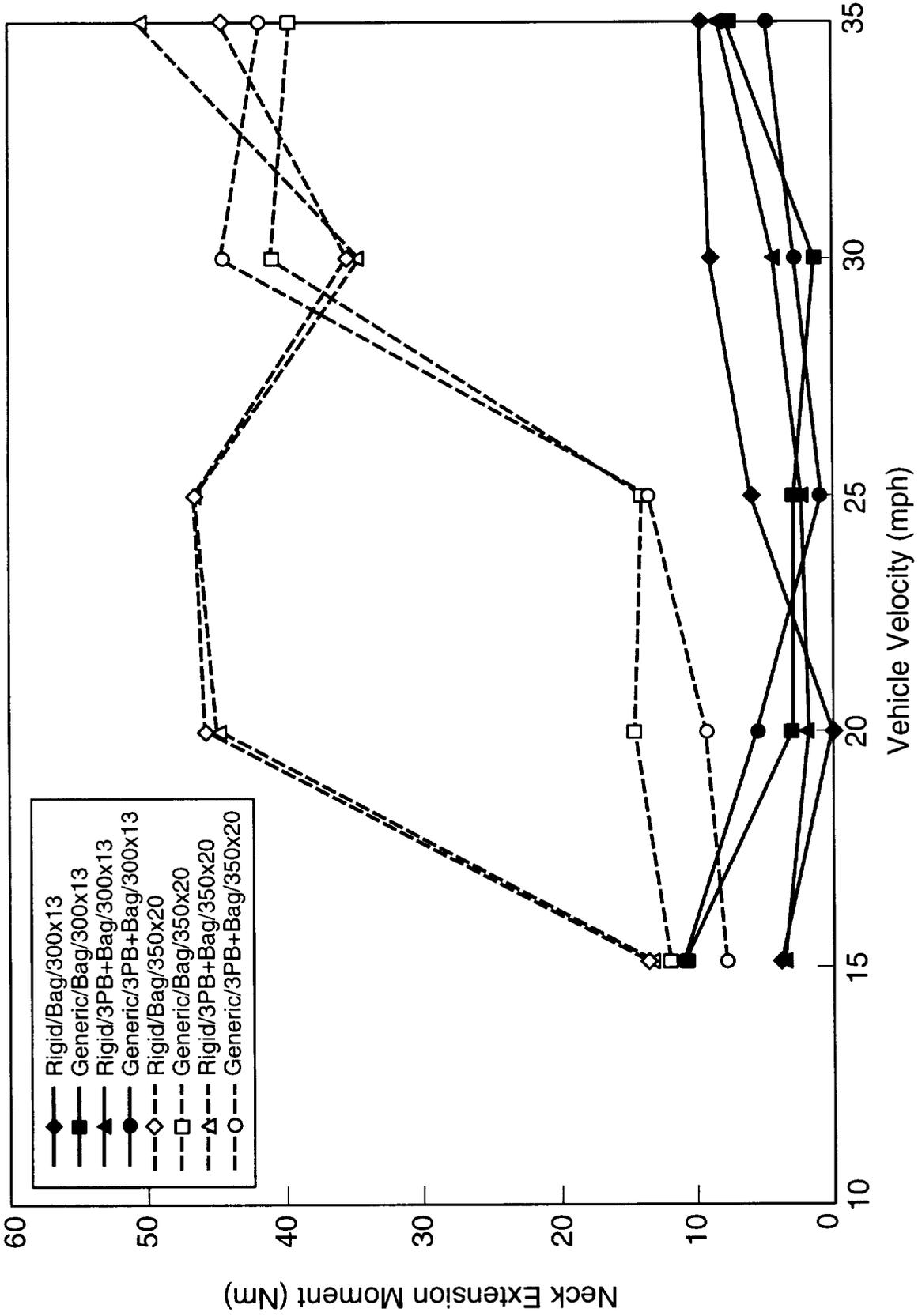


Figure F-7. Neck Extension Moment of 5% Female as a Function of Vehicle Velocity (From Reference [8])

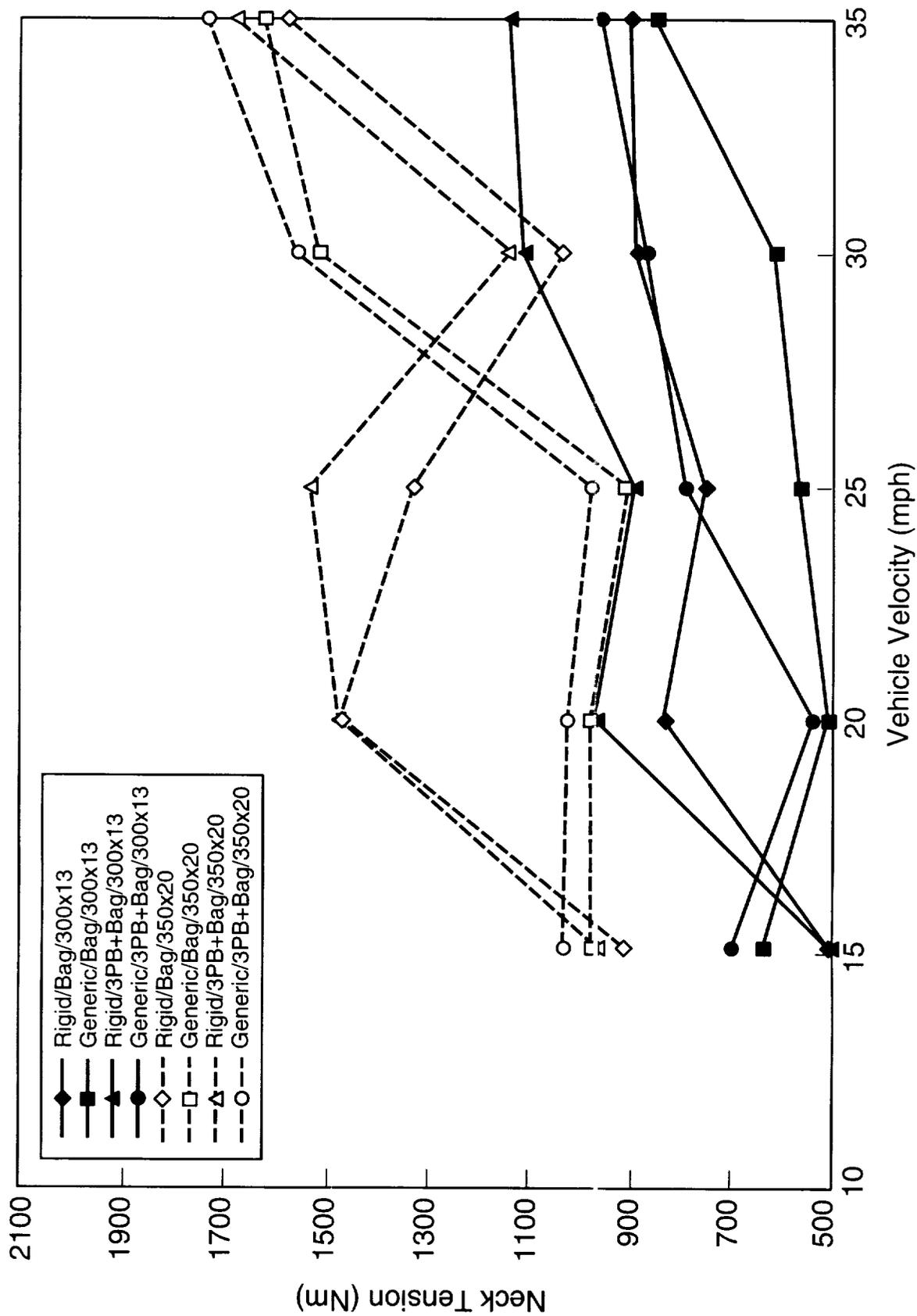


Figure F-8. Neck Tension of 5% Female as a Function of Vehicle Velocity (From Reference [8])

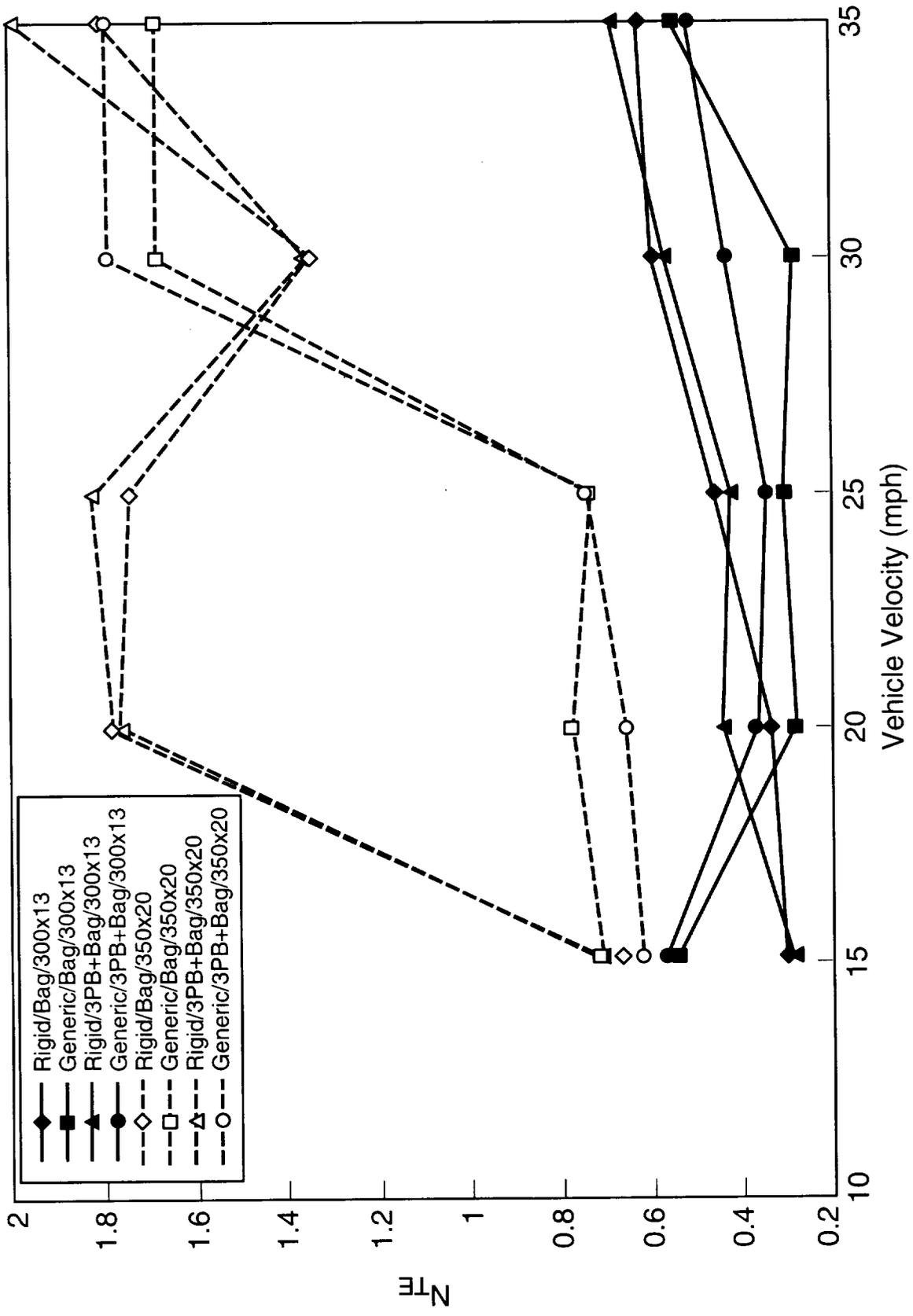


Figure F-9. N_{FE} of 5% Female as a Function of Vehicle Velocity (From Reference [8])

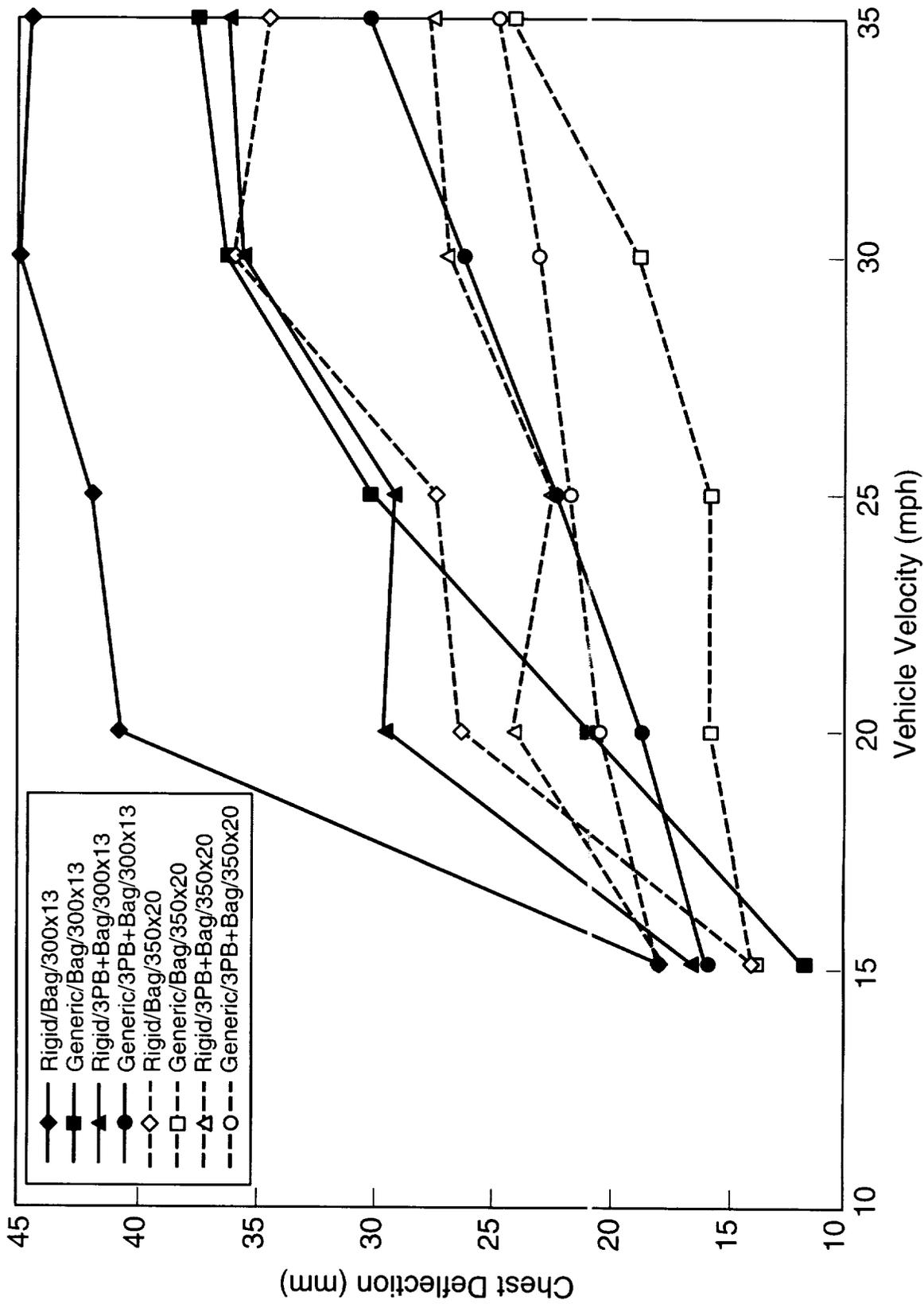


Figure F-10. Chest Deflection of 5% Female as a Function of Vehicle Velocity (From Reference [8])

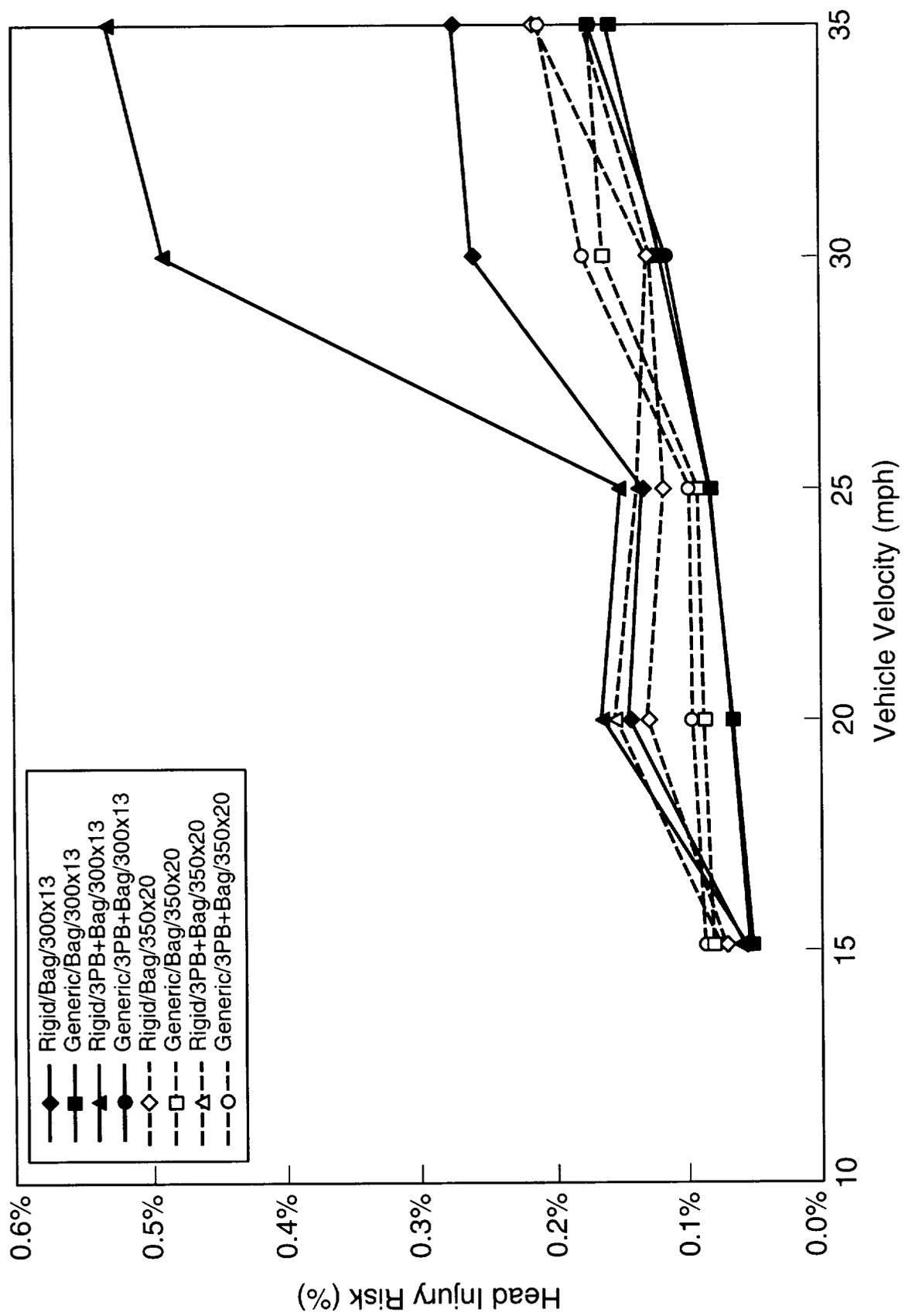


Figure F-11. Head Injury Risk of 5% Female as a Function of Vehicle Velocity (From Reference [8])

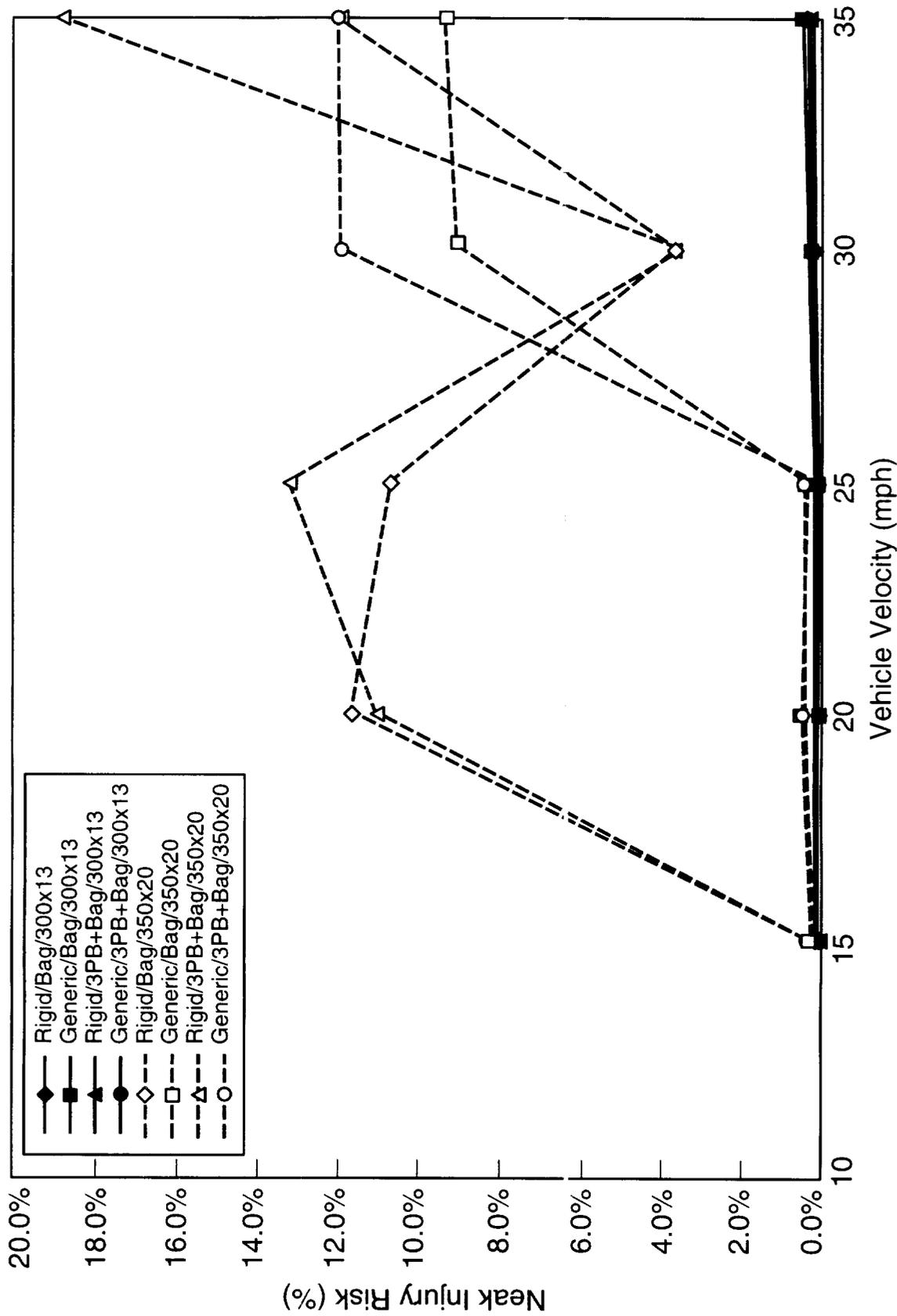


Figure F-12. Neck Injury Risk of 5% Female as a Function of Vehicle Velocity (From Reference [8])

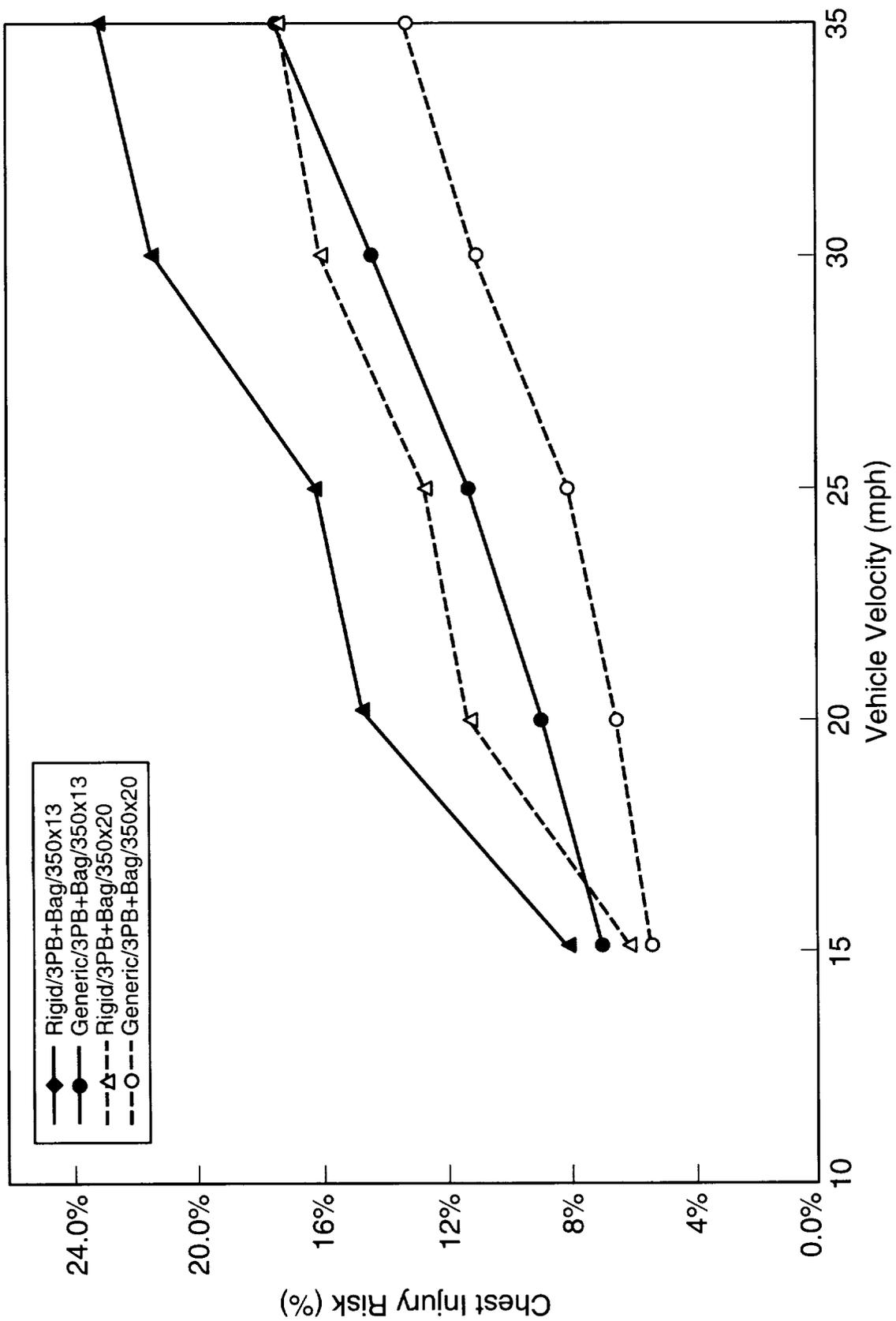


Figure F-13. Chest Injury Risk of 5% Female Due to Shoulder Belt Loading of Vehicle Velocity (From Reference [8])

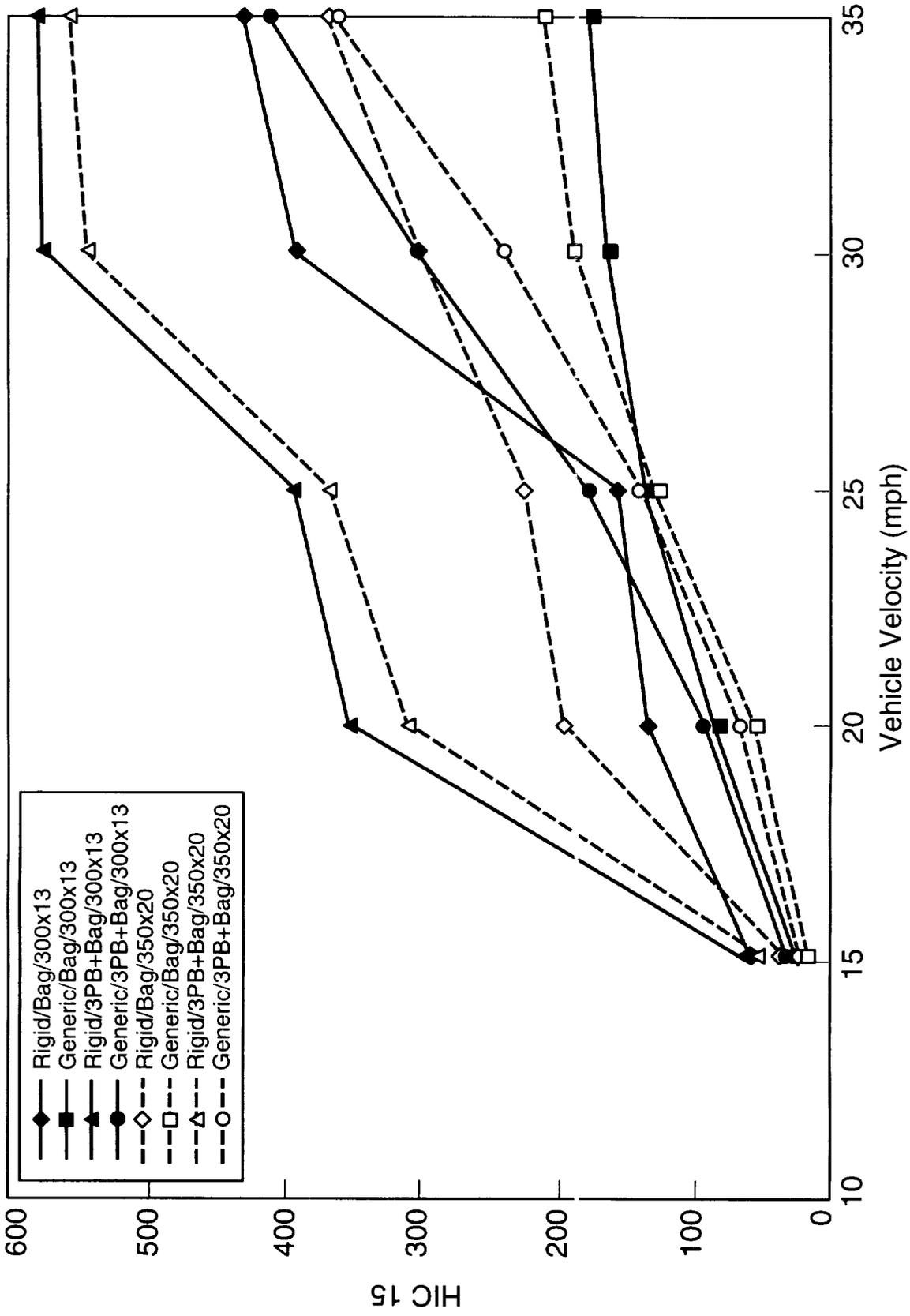


Figure F-14. HIC 15 of 50% Male as a Function of Vehicle Velocity (From Reference [8])

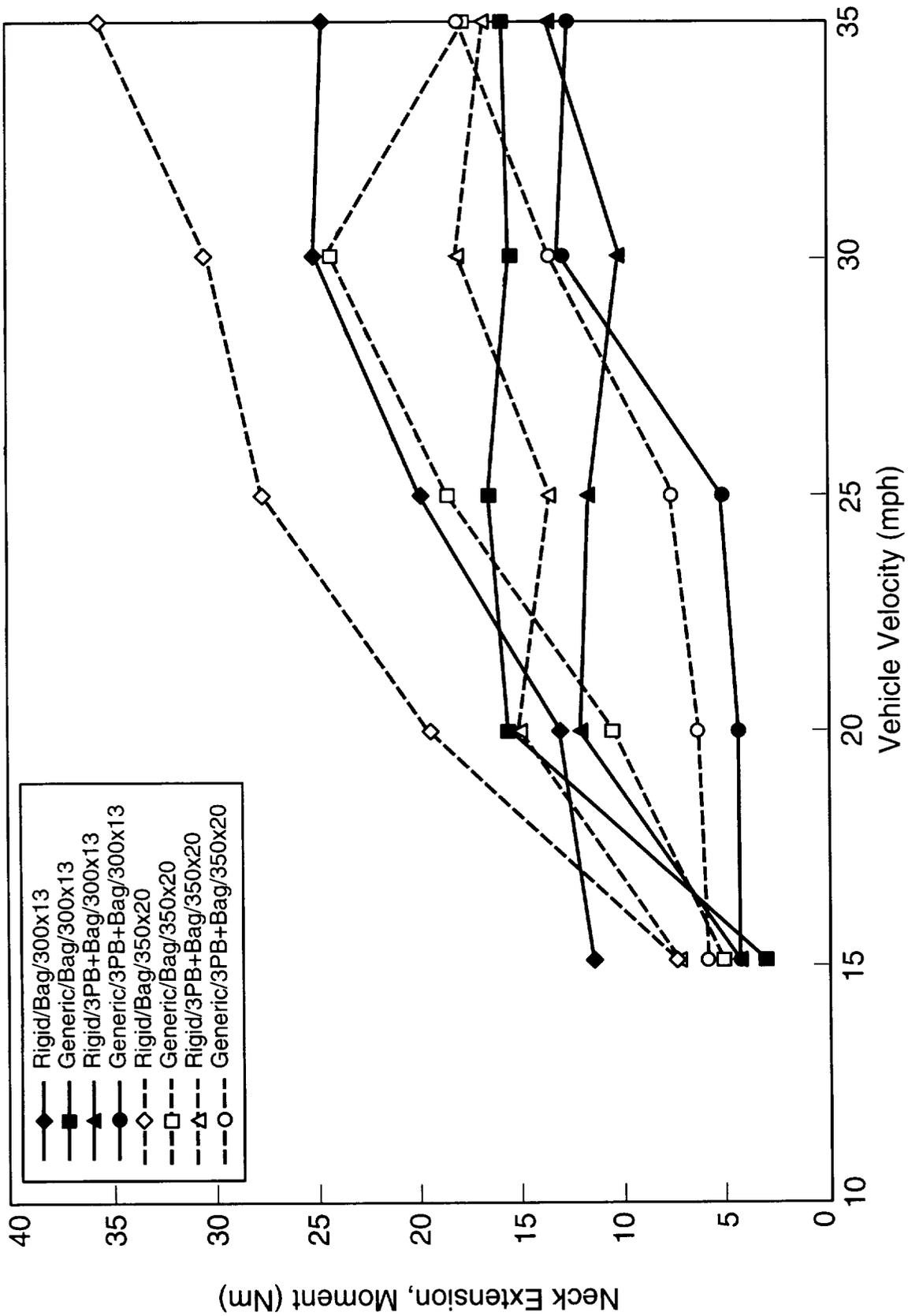


Figure F-15. Neck Extension Moment of 50% Male as a Function of Vehicle Velocity (From Reference [8])

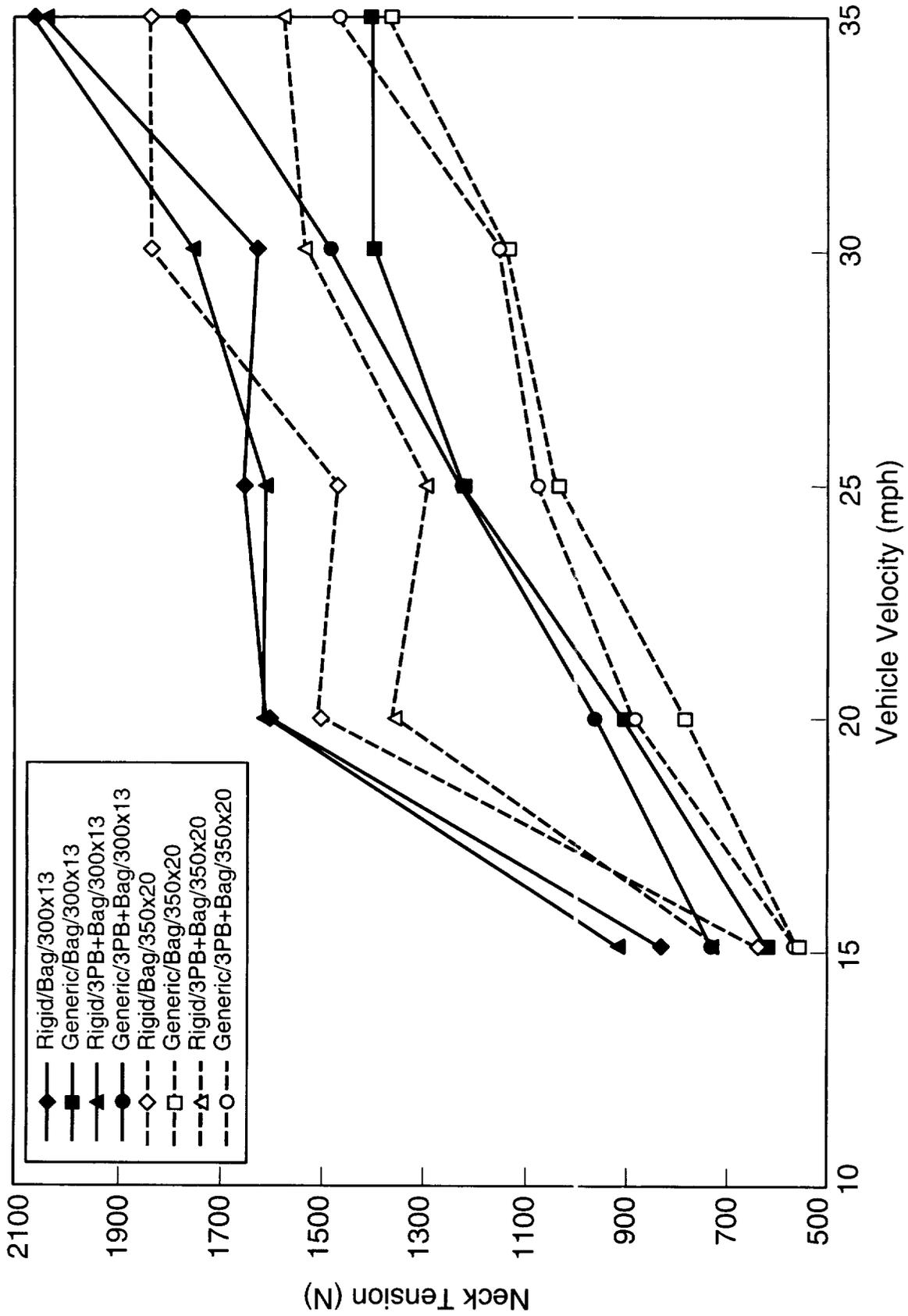


Figure F-16. Neck Tension of 50% Male as a Function of Vehicle Velocity (From Reference [8])

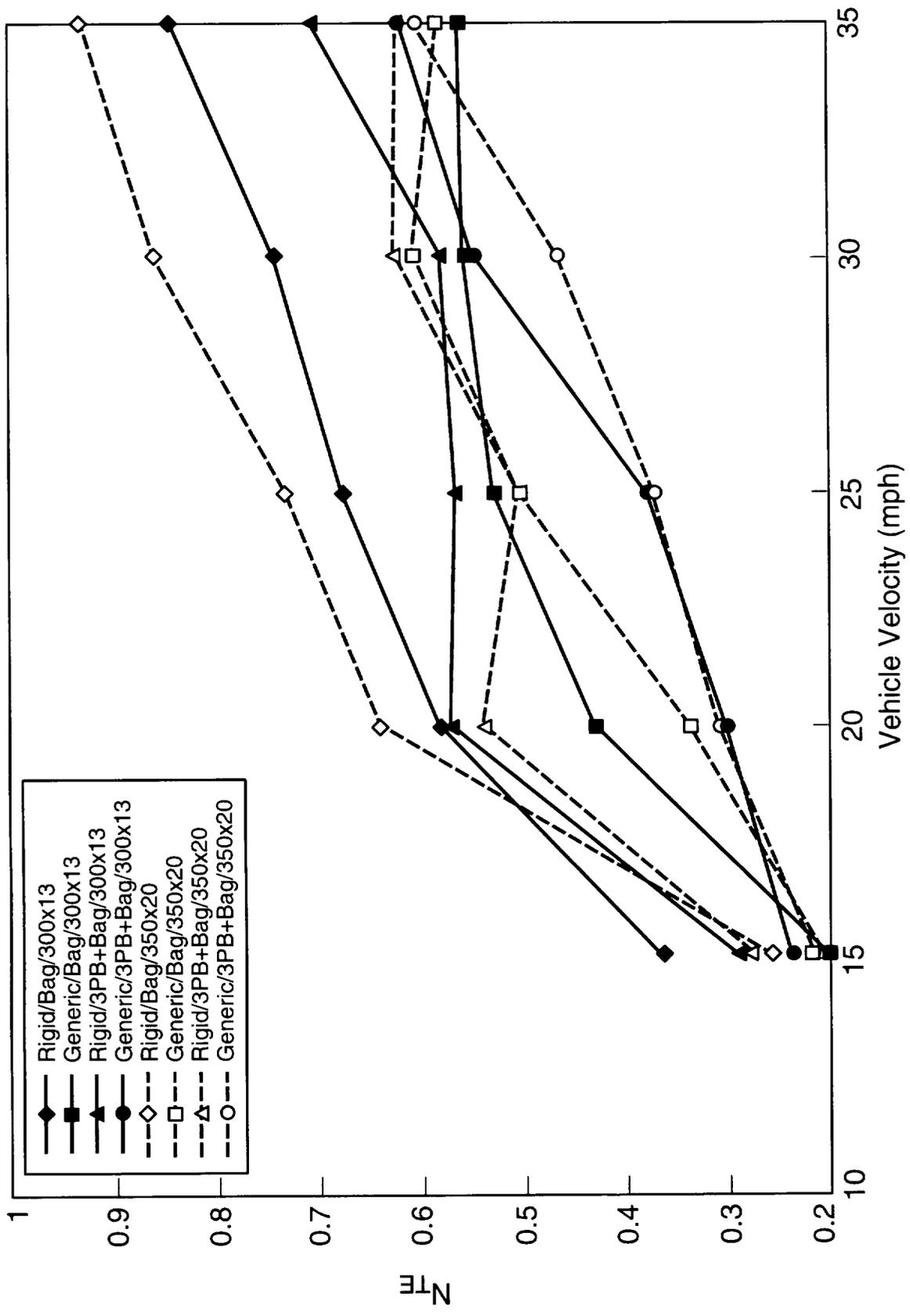


Figure F-17. N_{TE} of 50% Male as a Function of Vehicle Velocity (From Reference [8])

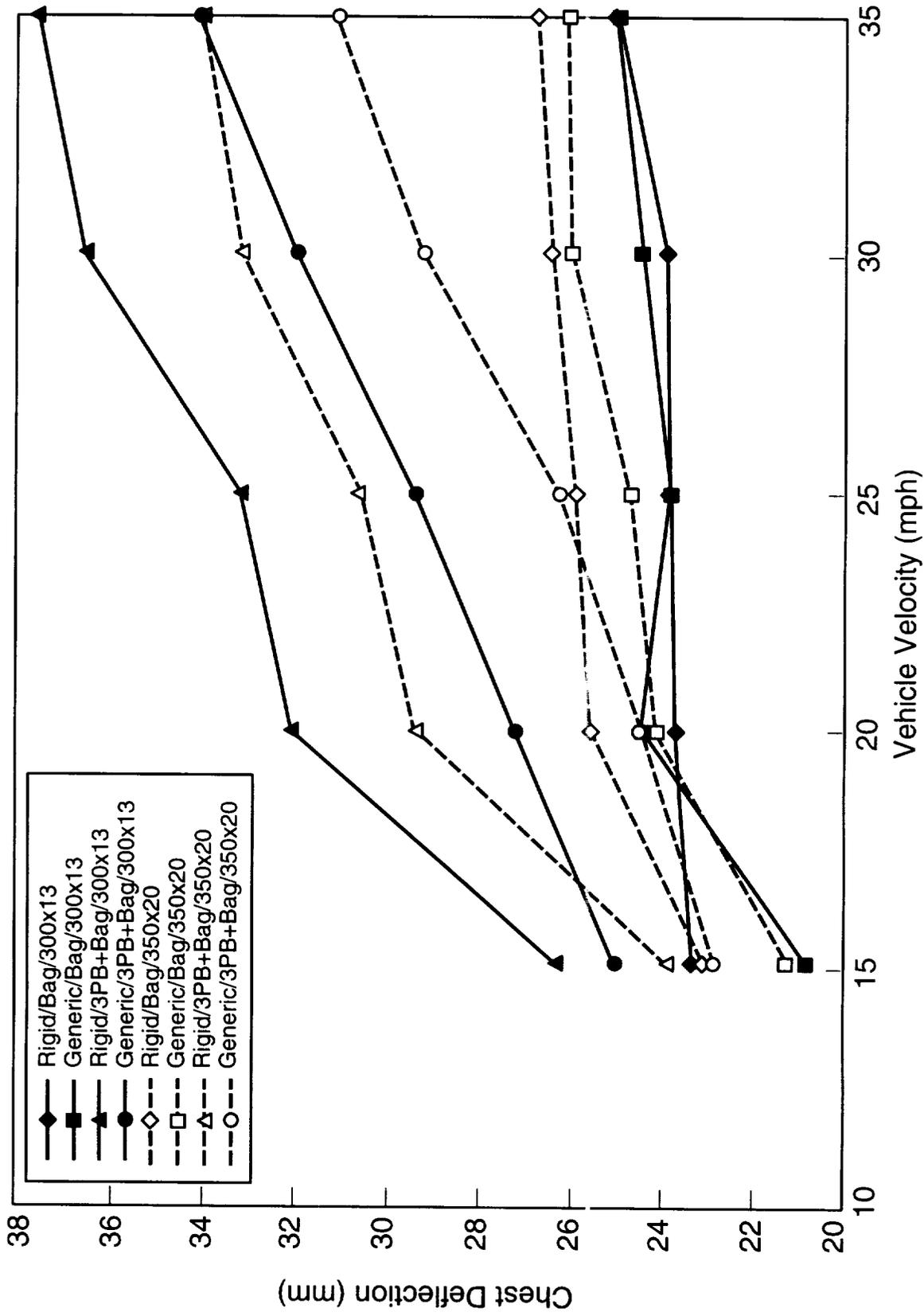


Figure F-18. Chest Deflection of 50% Male as a Function of Vehicle Velocity (From Reference [8])

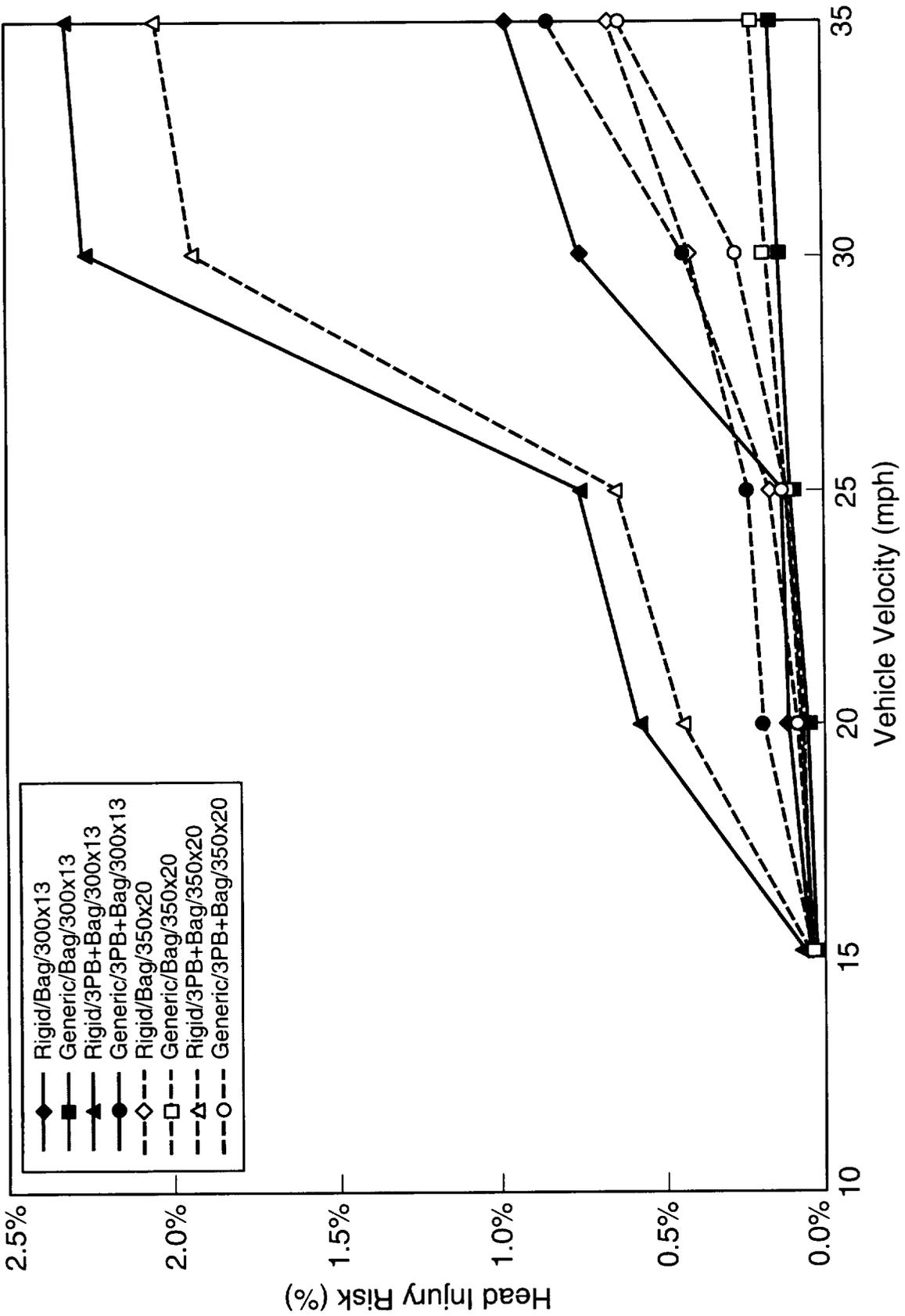


Figure F-19. Head Injury Risk of 50% Male as a Function of Vehicle Velocity (From Reference [8])

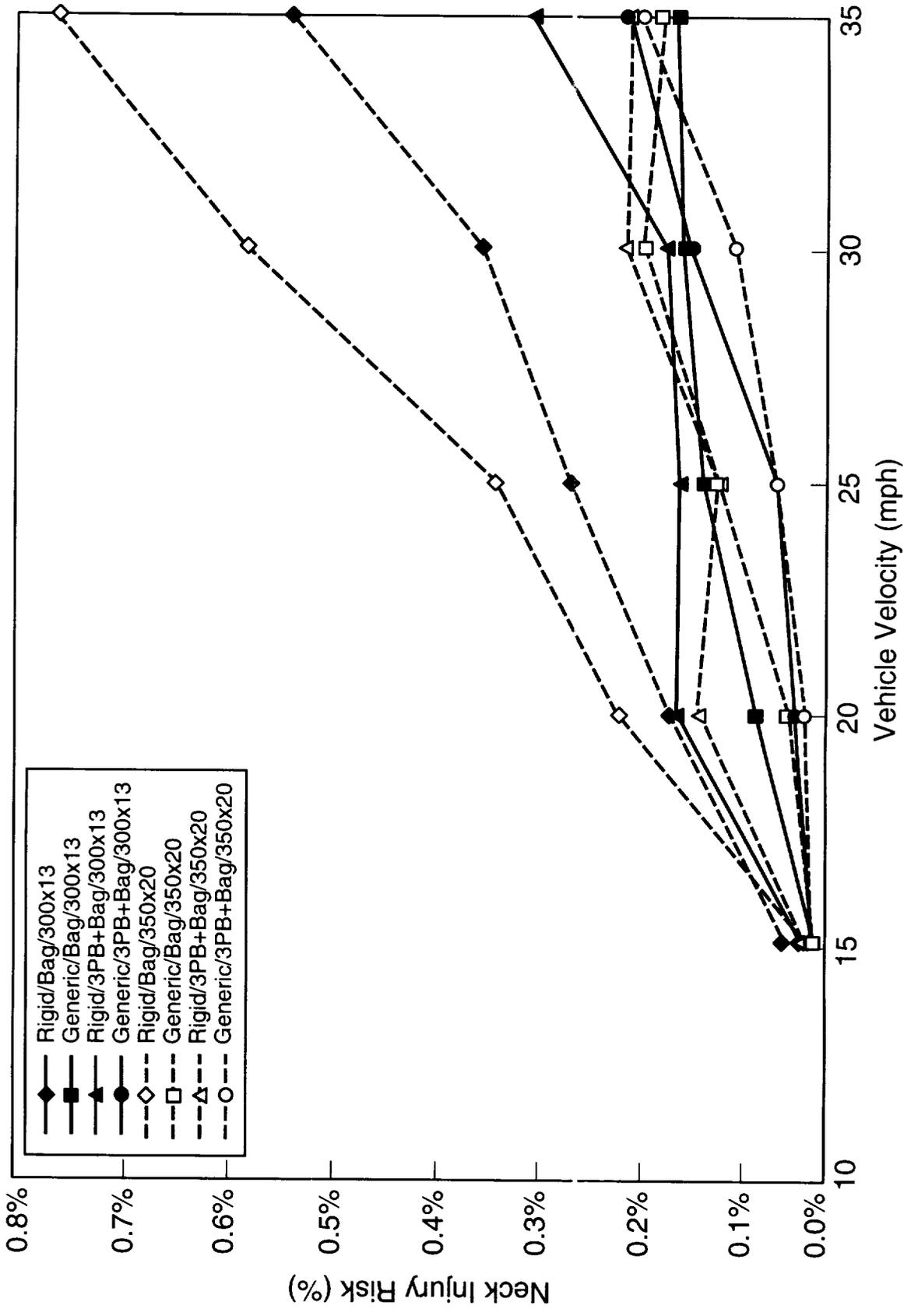


Figure F-20. Neck Injury Risk of 50% Male as a Function of Vehicle Velocity (From Reference [8])

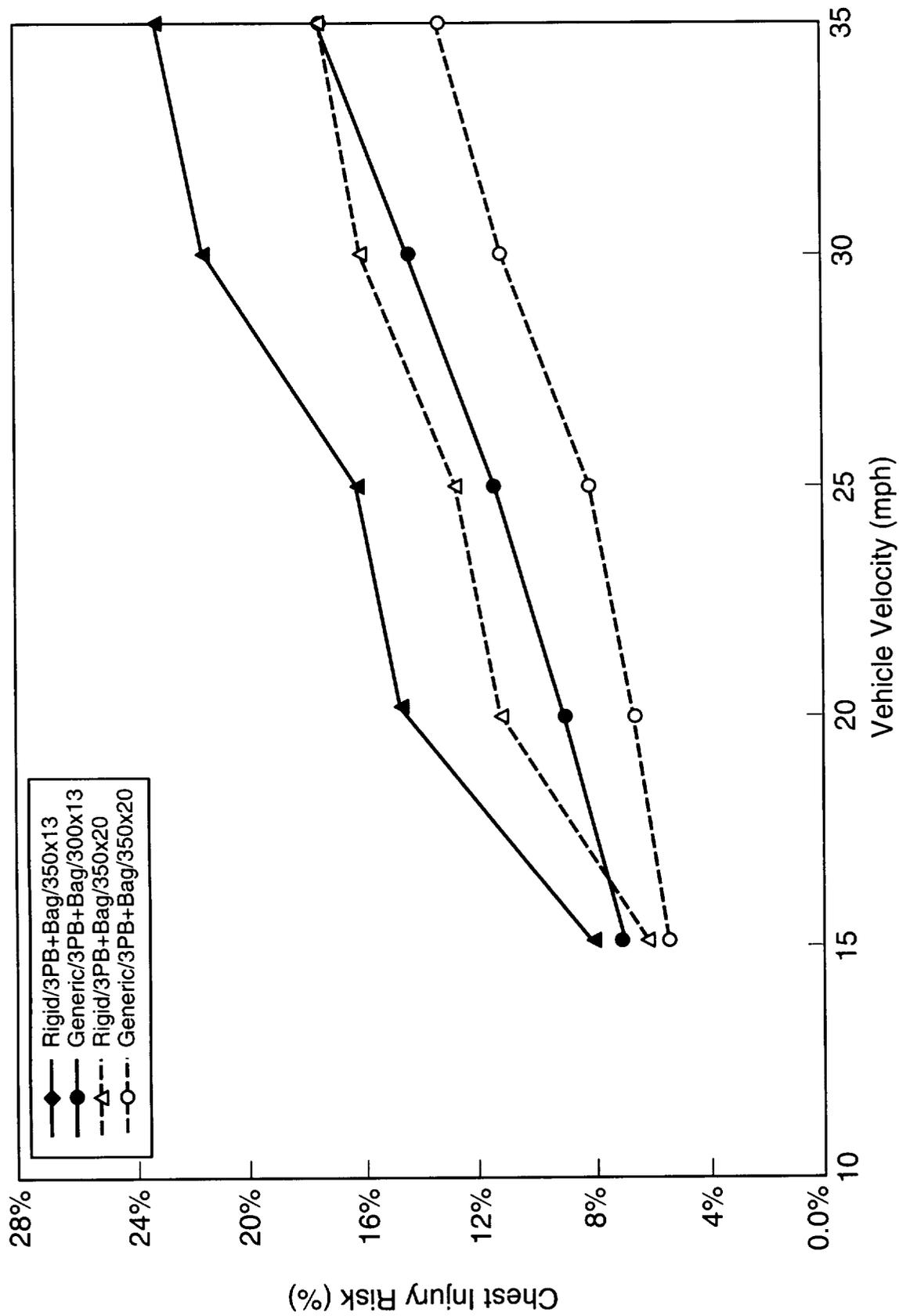


Figure F-21. Chest Injury Risk of 50% Male as a Function of Vehicle Velocity (From Reference [8])

APPENDIX G—ABBREVIATIONS AND ACRONYMS

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AAMA	American Automobile Manufacturers Association
AIAM	Association of International Automotive Manufacturers
AIS	Abbreviated Injury Scale
ARC	Ames Research Center
ATD	Anthropomorphic Test Device (crash test dummy)
CRABI	Child Restraint Air Bag Interaction
Caltech	California Institute of Technology
DOB	Deformable Offset Barrier
FARS	Fatal Analysis Reporting System
FFCS	Forward-Facing Child Seat
FFIS	Forward-Facing Infant Seat
FFRDC	Federally Funded Research and Development Center
FMVSS	Federal Motor Vehicle Safety Standard
FY	Fiscal Year
G	Acceleration of Gravity
GSFC	Goddard Space Flight Center
IAA	Interagency Agreement
IARV	Injury Assessment Reference Value
I ³	Inflation-Induced Injury
IP	Instrument Panel
IR	Infrared
HIC	Head Injury Criteria
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
km/h	kilometers per hour
kPa	kiloPascals
LaRC	Langley Research Center

LED	Light-Emitting Diode
LeRC	Lewis Research Center
LOVA	low vulnerability
MAIS	Maximum Injury for AIS
mph	miles per hour
MSFC	Marshal Space Flight Center
ms, msec	milliseconds
MVSRAC	Motor Vehicle Safety Research Advisory Committee
NASA	National Aeronautics and Space Administration
NASS	National Automotive Sampling System
NHTSA	National Highway Traffic Safety Administration
OEM	Original Equipment Manufacturer
OOP	Out-Of-Position
OSRP	Occupant Safety Restrain Partnership (USCAR)
PNGV	Partnership for a New Generation of Vehicles
psi	pounds per square inch
RFB	Rigid Fixed Barrier
RFCS	Rear-Facing Child Seat
RFIS	Rear-Facing Infant Seat
SAE	Society for Automotive Engineers
USCAR	United States Council for Automobile Research
VRTC	Vehicle Research Test Center (NHTSA)
WBS	Work Breakdown Structure
ΔV	delta V
V*C	Viscous Coefficient
5%F	5 th -Percentile Female (Dummy)
50%M	50 th -Percentile Male (Dummy)
95%M	95 th -Percentile Male (Dummy)

APPENDIX H—REFERENCES

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ADDENDUM

**NHTSA COMMENTS TO THE JPL ADVANCED AIR BAG
ASSESSMENT REPORT**

ADDENDUM

NHTSA COMMENTS TO THE JPL ADVANCED AIR BAG ASSESSMENT REPORT

Prior to publication of this report, an agreement was made by the National Highway Traffic Safety Administration (NHTSA), the National Aeronautics and Space Administration, and the Jet Propulsion Laboratory (JPL) that NHTSA would provide an insert to the final report that summarizes NHTSA's response and comments to the report. The attached document contains the agency response. The document first provides a summary table which contains the agency response to the 15 JPL recommendations contained in the final report. The document also contains overall comments to the final report including the characterization of human injury risks.

NHTSA: The Need for a Better Understanding of Restraint System Performance

JPL Recommendation		NHTSA Response
1	Continued restraint system assessment, with emphasis on restraint protection, and include consideration of costs and benefits.	Assessment of restraint systems has been underway in NHTSA through the agency's Special Crash Investigations, NCSA's semi-annual reports to Congress on occupant protection, Crash Injury Research and Engineering Network case studies, and research programs initiated specifically for evaluating restraint systems (such as safety belts, integrated seats, advanced air bags). These efforts will continue.
2A	Evaluate and quantify to the extent possible the benefits of the application of advanced technology to improve safety and protection of restraint systems with respect to injury risk of the full spectrum of occupants in the full range of crash severities experienced by the public.	NHTSA agrees that the benefits need to be evaluated. Safety benefits from the application of advanced technology are being evaluated through research and quantified consistent with agency practice through the agency's Office of Plans & Policy. Research programs, which provide data for the benefits analysis, are being conducted for a number of occupant sizes and a variety of crash severities.
2B	The benefits, costs and risks of advanced technology should be investigated and understood with respect to injury to head, neck, chest, and other body regions across the full range of occupant categories and crash severities.	The agency develops measures to gauge a range of injuries. For the various sized adult and child dummies utilized in the agency's crash tests of varying severity, the head, neck, and chest are three of the most important body regions generally evaluated, and will continue to be such, at least in the foreseeable future. It is the role of the agency to show feasibility of advanced technology and to assess the incremental benefits of selected advanced technologies. It is the role of manufacturers to test every advanced technology device that may be offered by them.

NHTSA: The Need for a Better Understanding of Restraint System Performance (cont'd.)

JPL Recommendation		NHTSA Response
3	Expand the assessment of advanced technology to crashes other than frontal crashes that were the focus of this assessment.	NHTSA agrees that in the future expanded assessments are warranted within the context of overall priorities and resources. In addition to expanding frontal crash conditions to include evaluation of performance in collinear and oblique offset impacts, research has been underway in NHTSA to evaluate system performance in other crash modes such as side impacts and in rollovers.
4	Develop a systematic vehicle test protocol that (a) incorporates measurements for comprehensive injury risk evaluation (head, neck, chest, etc.) for the 5th-percentile female, 50th-percentile male, and 95th-percentile male drivers as well as the full spectrum of passengers, and (b) includes crash severities representative of the full range of "real world" collisions.	NHTSA agrees that the test protocols should be expanded. The agency has long recognized this need and efforts have been initiated to include dummies representing the population at large, and toward including test procedures that cover the wide spectrum of crashes that occur in the real world. However a complete evaluation of every scenario requires enormous resources. To the extent possible, the agency conducts evaluations of a variety of crash conditions.
5	Evaluate the impact on air bag performance of deployment time variability, inflator variability and system and component reliability for any advanced technology. Again, the full range of occupant size and crash severity that represent use by the general public must be considered.	NHTSA establishes minimum overall system performance in its safety standards. Manufacturers are responsible for vehicle system reliability. To the extent that it is shown that there is inherent variability that can not be limited, this may be taken into account in setting standards. Assessment of systems on various occupant sizes in different crash severities is expected to be part of future evaluations.

NHTSA: The Need for Better Real-World Data

JPL Recommendation	NHTSA Response
<p>6</p> <p>Expand the National Automotive Sampling System (NASS), and revisit the question of how it should be structured and what procedures should be used to provide data needed for safety diagnosis and engineering analysis.</p>	<p>NHTSA generally agrees. NHTSA has included in its Strategic Execution Plan, Goal 4C to improve NHTSA's timely use and analysis of available data; and regularly reevaluate data needs, how they are being met, and how future data collection can be improved. In FY 1998, NHTSA plans to initiate a review of the FARS, NASS GES and NASS CDS to provide an assessment of these systems and identify practical improvements to current and potential crash data collection procedures, techniques, and policies. We are also working toward uniform data sets for the FARS and NASS programs with comparable data elements where applicable. The NASS program converted from paper data collection to electronic data collection in January 1997 with an Oracle relational database as the framework and penbased laptops and digital cameras for documenting data in the field. This is expected to make more detailed, accurate and useful data available for safety diagnosis and engineering analysis in a more timely manner.</p>
<p>7</p> <p>Study the feasibility of installing and obtaining crash data for safety analyses from crash recorders on vehicles.</p>	<p>NHTSA agrees that this may warrant reconsideration in the context of the agency's overall priorities. The agency considered this issue during the mid 1970's and concluded that it was not feasible because of cost and privacy issues. From a technological perspective, the current situation may allow data from crash recorders coupled with existing data systems to provide more detailed field data. NHTSA has formed a committee to investigate the possibilities of using crash information collected in the vehicle in safety research. The committee plans to focus on understanding the operation of current event data recorder (EDR) systems, their technical limitations, and what crash information is currently available. The committee will consider developing technical requirements and guidelines that would establish criteria for the next generation of EDR's.</p>

NHTSA: The Need for a Better Understanding of the Future Potential of Technology

JPL Recommendation		NHTSA Response
8	Evaluate specific technologies that have promise of significant safety benefit, such as:	
8A	Pre-crash sensors—both separately and coupled with the crash-avoidance sensors now being investigated—which could provide improved crash type and severity sensing.	NHTSA agrees that the enhancement of pre-crash sensors is important. The agency has already done assessment work in this area and we plan to undertake further work. Equipment suppliers and manufacturers should play a lead role in development.
8B	Advanced belt systems and air belts that could improve protection, but have been neglected because of the emphasis on air bags.	NHTSA had introduced air belts in its Chrysler/Calspan Research Safety Vehicle (RSV) in 1978 and found them to be effective in our tests. Belt systems are very effective when used and used properly. We believe that performance is enhanced when coupled with pretensioners, integrated systems, etc. Equipment suppliers and manufacturers should play a lead role in development. The agency has expended considerable effort to expand safety belt usage and is assessing improvements, in part in the context of safer air bag systems.
8C	Air bag/inflator designs that could eliminate the keep-out zone and the information (sensors) required to support the functioning of the design.	NHTSA agrees technologies have been identified. Technologies need to be developed and refined to eliminate “false” positives or negatives (shut offs when systems are actually needed or systems being on when not needed). Equipment suppliers and manufacturers should play a lead role in development.

Industry: The Need for Continued Advanced Technology Development

JPL Recommendation		NHTSA Response
9	Continue diligent effort to implement the advanced technologies that have been shown to JPL, because those technologies will make restraint systems safer and more protective.	NHTSA agrees that implementation of advanced technologies will lead to a greater safety benefit for the range of occupant sizes over the range of crash severities. However, NHTSA recognizes that this is the responsibility of manufacturers to implement technologies.
10	Reduce the deployment time and inflator mass flow variabilities; otherwise these variabilities will have detrimental effects on advanced air bag system effectiveness.	NHTSA's interest is in the overall performance of the system. Vehicles themselves have been found to be variable. Therefore, while in theory it is agreed that sub-system variability can be an important factor, it needs to be assessed in the context of the overall system. It should be a concern for sub-system suppliers and auto manufacturers. Improved air bag deployment timing will reduce the potential for air bag induced injuries to out-of-position occupants.
11	Continue diligent efforts to increase restraint system reliability.	NHTSA agrees. Efforts to address a range of crash conditions are ongoing. Developing systems to meet the requirements will lead to inherently better reliability.

NHTSA/Industry: Cooperative Efforts

JPL Recommendation		NHTSA Response
12	Develop quantitative goals for safer and more protective restraint systems that address air-bag-induced injuries and protection in high-severity crashes.	NHTSA agrees. NHTSA is addressing a range of crash conditions, from low speed crashes where air bag induced injuries more commonly occur to the high speed crashes where air bags are most effective.
13	Continue to develop and refine biomechanical injury criteria for restraint systems using the best science available.	The biomechanical injury criteria NHTSA has incorporated are based on considerable study and assessment. The agency's standards are developed based on the best information at hand and we upgrade the requirements based upon the most up to date information.
14	Develop protocols and procedures for testing air bag systems to ensure air bag system robustness.	NHTSA generally agrees. Research programs have been initiated to develop test procedures for evaluating vehicle systems including air bag system's robustness over a range of occupant sizes and crash severities.
15	Inform the public of the specific risks associated with each vehicle air bag, e.g., by providing the keep-out zone dimensions, and recommend ways to mitigate the risk.	We do not believe that it is possible to assess all risks associated with each vehicle/air bag system given the broad range of potential crashes and occupant positions. General ways to reduce risk have been identified. Even if it were possible to assess all risks, such an assessment might lead to misinterpretation by the public. Any keep-out zone information or any other pertinent information about air bag risks themselves would have to be accompanied by the air bag/vehicle system's safety potential under a variety of conditions. This approach would also provide no information about the performance of the air bag sensor (i.e., the frequency of unnecessary deployments in low severity crashes of a particular vehicle), the crashworthiness of the vehicle, etc. NHTSA has spent considerable effort informing the public regarding personal actions that can be taken to reduce the risk of air bag induced injury, and will continue to recommend practices available in the future.

OVERALL COMMENTS TO THE ADVANCED AIR BAG ASSESSMENT REPORT

NHTSA had numerous comments to the JPL Advanced Air Bag Assessment Report. While some comments were in agreement with JPL's assessment, others were not. There was one major point of contention between NHTSA and JPL that both parties, at the conclusion of the project, agreed to disagree upon. This was the report's discussion of human injury risk criteria. The following section briefly discusses the agency's position on this issue.

Human Injury Risk Criteria

The agency recognizes and agrees with JPL that valid human injury risk criteria are necessary. However, much of the discussion and many of the conclusions reached by JPL in Appendix E, Human Injury Risk Criteria, cannot be accepted because of JPL's use of results obtained by procedures that have not been accepted or adopted. In particular, JPL used the ad-hoc Mertz/Weber analysis procedure for developing injury risk criteria. The agency feels that the injury relationships applied by JPL are not the best representations of the available data. NHTSA will develop and rely on criteria obtained using what it believes to be more rigorous analytical procedures. Furthermore, the injury criteria currently specified by the agency's mandated Federal motor vehicle safety standards have undergone a lengthy developmental process in which comments submitted in the course of rulemaking have been given careful consideration before the final determination on the criteria.

One particular example of rulemaking regarding injury criteria is that in which the currently used 36 millisecond time duration for the Head Injury Criterion (HIC) was selected. HIC is a complex calculation involving finding the maximum value of a mathematical function using the head acceleration response measured on a dummy during a crash test. The maximum value of this function has been shown to be highly correlated to the probability of head injury. Prior to this rulemaking, the calculation procedure involved finding the maximum value over any time duration of the head acceleration response. The agency undertook this rulemaking as a result of a petition from Ford Motor Company to limit the HIC calculation to a 15 millisecond maximum duration. The basis for the Ford petition was their contention that the research that led to the development of HIC involved head impact to rigid surfaces and the duration for these impacts were approximately 15 milliseconds in duration, and hence the calculation should be limited to a maximum time duration of 15 milliseconds.

In August 1986, the agency rejected the proposed 15 millisecond time interval and instead chose a 36 millisecond duration for calculating HIC. This alternative was selected for a number of reasons. The agency determined that neck loads and peak head accelerations would increase by 33 percent if the shorter 15 millisecond duration were selected, thereby resulting in an increased probability of head and neck injuries in real world crashes. More importantly, however, the agency determined that only a small fraction of brain injuries occur in the real world in the 15 millisecond or less duration. Whereas in many real world crashes that are similar to the tests that the agency conducts, the agency determined from evaluation of these tests that the head contacts involved longer time durations, i.e., in the range of the 36 milliseconds. Hence the 36 millisecond time interval was selected.